METHODOLOGICAL NOTES

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On the redefinition of the kilogram and ampere in terms of fundamental physical constants

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Contents

Abstract. In the summer of 2005, a meeting of the Consultative Committee for Units of the International Committee on Weights and Measures took place. One of the topics discussed at the meeting was a possible redefinition of the kilogram in terms of fundamental physical constants — a question of relevance to a wide circle of specialists, from school teachers to physicists performing research in a great variety of fields. In this paper, the current situation regarding this question is briefly reviewed and its discussion at the Consultative Committee for Units and other bodies involved is covered. Other issues related to the International System of Units (SI) and broached at the meeting are also discussed.

1. Introduction

The metric system of measures emerged soon after the Great French Revolution and gradually became the predominant international system of units in industry, commerce, teaching, and science. As time passed, following progress in physics, it underwent substantial changes. Nevertheless, even today, in the 21st century, one of the base SI units, the kilogram, is still defined via an artifact — an artificially created standard. It must be said that the kilogram is not an isolated unit — it is used to define three other base SI units: the ampere, the mole, and the candela. This means that we are speaking here of the *majority* of the base units of the SI.

The conceptual drawbacks of such a standard for the kilogram are obvious: it is accessible only in one place, BIPM (the French abbreviation for the International Bureau on Weights and Measures) in Sèvres, near Paris; it could, in principle, be destroyed or lost, and the fear of this explains the extremely limited accessibility (it has been used only three times in about hundred years); there is a need to store and use it in air, which in itself is dangerous, and the standard may age and change its properties. But this standard has one merit — it is impossible (and always was) to build a natural standard of mass with better technical characteristics.

In view of the drawbacks of the modern kilogram standard, over the years various suggestions have been made as to redefining the standard in more fundamental and natural terms. Such a possible redefinition of the kilogram, the ampere, and some other SI units became the key issue at the last annual meeting of the CODATA Task Group on Fundamental Constants and the 17th meeting of the Consultative Committee for Units (CCU) of the International Committee on Weights and Measures (CIPM). [1]

The discussion was initiated by a recent suggestion of this kind (see Ref. [1]), but was not limited to it. The Consultative Committee for Units was supposed to prepare recommendations for the October 2005 meeting of CIPM, whose decisions in turn were to be approved at the General Conference on Weights and Measures (GCWM) in 2007. The next meetings of CIPM and GCWM are to be held in 2009 and 2011, respectively. The meetings of CCU and the CODATA Task

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[1] At the end of the paper there is a list of abbreviations and full names of the various international bodies mentioned here.

Group on Fundamental Constants were held in Sèvres, near Paris, from June 29 to July 1 and on June 28, 2005, respectively.

This paper is devoted to a discussion of the situation that has emerged in the area of precision measurements related to the definition of the kilogram, and a brief report on the results of the meetings at which this problem was discussed. The Consultative Committee for Units has also examined the new edition of the SI brochure, and a selection of changes in it are also mentioned in the present paper.

2. Precision measurements of masses and electrical quantities

There is a certain similarity between the current situation and the situation of about two decades ago, in the 1980s, when the modern version of SI was adopted (see Ref. [2]). At that time, experiments on determining the speed of light, in which the krypton emission wavelength (which formed the basis of the 'old' meter) was compared with the frequency of a hyperfine transition in caesium, proved to be so successful that inaccuracy in determining the meter became the main source of uncertainty in such experiments. The problem was resolved in 1983 with the introduction of a new definition of the meter in which the speed of light in vacuum was fixed and the meter was set equal to 1/299 792 458 of the length of the path travelled by light in vacuum in one second (see Ref. [3]). Here and in what follows, by fixed we mean the adoption of a certain exact numerical value of a quantity by definition.

The current situation with the base units of the SI is qualitatively different, and the above similarity is of course out of place. In Ref. [4], I briefly described the current situation, and that paper is an extended version of the working document CCU/05-27.

The idea of a metric convention and its implementation in the form of SI, and the creation of various organizations such as BIPM and CIPM, was all aimed at ensuring a consistent measurement of all quantities in a single self-consistent system of units, SI. However, despite the fact that the latest version of SI was adopted in 1983, already in 1988 CIPM arrived at a decision, approved by GCWM in 1990, that concerned the use of a different version of SI in precision electrical measurements [5] (see also Ref. [6]).

This other version of SI is based on two units known as practical units, ohm-1990 and volt-1990, in terms of which the Planck constant h and the elementary charge e have exact values, known by definition, that satisfy the following conditions

$$R_{\mathrm{K}} = \frac{h}{e^2} = 25\,812.807\ \Omega_{90}\,,$$
$$K_{\mathrm{J}} = \frac{2e}{h} = 483\,597.9\ \mathrm{GHz}\ \mathrm{V}_{90}^{-1}\,, \tag{1}$$

where R_{K} and K_{J} are the von Klitzing and Josephson constants, respectively.

In this version of SI, the magnetic constant μ_0 becomes measurable, while the 'electrical' analog of the kilogram, namely

$$1\ \mathrm{V}_{90}^2\ \Omega_{90}^{-1}\ \mathrm{s}^3\ \mathrm{m}^{-2} = \left[1 + 1.0(1.7)\times 10^{-7}\right]\mathrm{kg}\,, \tag{2}$$

differs somewhat from the SI kilogram.

Thus, it turns out that for a long time we have been left without a system of units that can be applied to all measurements. The standard version of SI is used in macroscopic measurements of mass, while practical units are applied in precision electrical measurements. When microscopic measurements of mass are involved, we actually use the practical units as well. Strictly speaking, the result of measuring the mass of a particle or atom expressed in electron-volts will be more exact if we employ the volt-1990 unit rather than the standard volt. The reason is that the measurement error proper may be (and often is) smaller than the uncertainty in determining the units. A similar situation emerges when one has to convert the results expressed in atomic mass units. Converting atomic mass units into kilograms is less accurate than, say, converting into electronvolts, provided that the volt-1990 unit is applied.

It is symptomatic that this practice was introduced by the same bodies whose duty is to ensure unification in measurements. This is the result of the certain helplessness concerning the experimental situation. Why is it not possible to use only one system of units? The problem here is that experiments similar to those pursued to determine the speed of light, involving different areas of measurements, are not very accurate. In contrast to the case where the speed of light was fixed, in the case at hand the areas of measurements are more complex and several types of experiments serve as links between these areas. What is more important is that the areas of measurement are not independent.

There are only two independent parameters, for which we can take, say, the mass $m(\mathcal{K})$ of the kilogram prototype and the value of the constant μ_0. By setting these parameters we specify the units in both areas of measurements (masses and electrical quantities). An alternative definition fixes the values of two fundamental quantities, say, the Planck constant h and the elementary charge e. When one pair of values is fixed, the other must be found through experiment. In the standard version of the SI, we deal with experiments determining the fine-structure constant

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \tag{3}$$

and the Planck constant. If we fix h and e, to determine the mass of the kilogram prototype and μ_0 we must carry out the *same* experiments that are now used to determine α and h.

3. Constants and units

What is the meaning of the above quantities from the practical viewpoint? In practice, the mass of the kilogram prototype defines the unit of measurement of all macroscopic masses, and since the main way to compare such masses is to weigh them, to determine all masses within a rather wide range we must in some way determine one of them (say, the mass of the kilogram prototype) and have good scales.

The value of μ_0 is not used in practice for measuring currents. This quantity (more exactly, ε_0) is applied to create what is known as a calculable capacitor, the macroscopic standard of the farad.

Realizing the farad, we can proceed to the ohm, but a more successful approach is based on the quantum Hall effect within which all resistances are compared with R_{K}, which in practical units is known exactly. On the basis of the ohm-1990 we can determine the corresponding unit of capacitance, Thus, the ohm-1990 and the farad of SI are natural competitors, and this also follows from the relationship

$$R_K = \frac{c\mu_0}{2\alpha}\,, \tag{4}$$

which makes it possible to fix the value of either R_K or μ_0 but not the two constants simultaneously. These standards are the implementation of two competitive approaches. The calculable capacitor is a classical macroscopic device whose properties vary with time, as those of any classical object. The term 'calculable' stands for a certain idealized situation, which means that all possible deviations from such a situation must be closely monitored. On the other hand, a standard based on a macroscopic quantum effect (the quantum Hall effect), whose dimensions are characteristic of classical physics, nevertheless has characteristics that are quantized and, hence, do not vary with time. Comparison of these two types of standards irrevocably speaks in favor of the quantum standard.

In practice, voltage is measured by the Josephson effect in volt-1990 units. To measure electric currents, a unit defined in terms of the practical ohm and volt is employed, but this unit is not directly included in the CIPM recommendations, so we should speak of the ampere-1990 unit with certain caution.

A consistent system of units assumes that one pair of quantities is assumed to be known exactly by definition, while the other pair is found from experiment. The problem, however, lies in the fact that the high-precision measurement of the other pair of quantities is impossible.

Progress made in recent years has not influenced the situation in general, but certain details have changed considerably. The accuracy of electrical measurements in practical units has increased, and so has the accuracy of experiments that link different areas of measurements.

Modern accuracies are as follows:

• measurements of masses: the mass of the standard [2] does not likely vary by one unit (or by several units) at the eighth decimal place; for practical applications, several units at the seventh decimal place are sufficient; masses on the order of a kilogram can be compared with a much higher accuracy;

• measurements of electrical units: in practical units, the error is at the ninth decimal place; such precision measurements are important for the use of electrical phenomena in various sensors (say, to monitor temperature and so forth);

• the accuracy of measuring the fine-structure constant α, corresponding to the accuracy of determining R_K with a known fixed value of μ_0 (or, in another version of the SI, corresponding to the accuracy of determining μ_0 with a known fixed value of R_K) amounts to several units at the ninth decimal place, and

• the accuracy of measuring h is the most precarious part of the scheme in any scenario: to within possible factors of 'twos' (factors of 2 or 1/2), [3] just this accuracy determines the accuracy of reproducing the ampere and volt in the modern version of the SI and will determine the accuracy of realizing the kilogram at fixed values of h and e; the errors are somewhat smaller than one unit at the seventh decimal place, but there is a discrepancy of about 1 ppm (see Fig. 1).

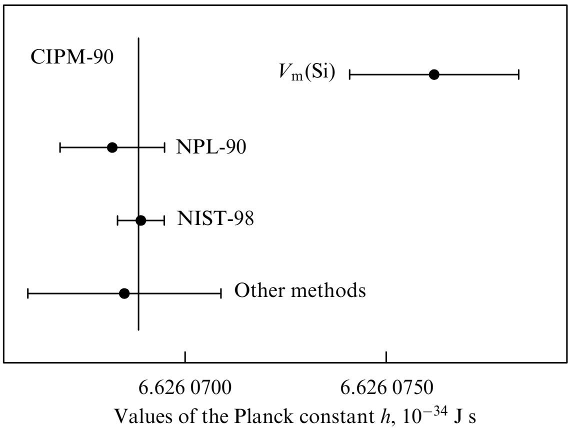

Figure 1. Determining the Planck constant h by different methods (cf. Ref. [4]). Two values belong to the watt-balance method (NIST-98 and NPL-90), one result is related to the Avogadro constant [V_m(Si)], and the results achieved by other methods are grouped into their mean value. All values have been taken from Ref. [7], except for the last one which has been obtained from the data in Ref. [7] by Peter Mohr. The vertical line marks the fixed value of h in practical units [5].

Clearly, in the situation at hand it is impossible to make all measurements in SI units without loss of accuracy. However, this does not mean that exact measurements cannot be made in all areas. As noted earlier, the solution amounts to making some measurements in practical units. If the redefinition of the kilogram is adopted, the mass of the kilogram prototype will become such a unit for a certain time.

It should be emphasized that the universal use of a unified system of units is, generally speaking, more in a convenience than anything else. If a measurement is made in arbitrary but strictly defined units (which actually is a common practice), from the scientific viewpoint it is no worse than a measurement that relies on SI units. However, the convenience of using a unified system of units and some additional universal units is colossal. There is a certain analogy here with traffic rules. Such a thing as traffic lights is, by itself, meaningless and can be replaced with any similar object. Nor does any rule by itself have any special meaning. However, the system of rules as a whole simplifies the traffic so much that its convenience and merits are obvious.

Of course, there is nothing wrong in using practical units. However, it is much simpler to speak of the volt than of the 'practical realization of the volt based on the Josephson effect with a fixed value of K_J'. The metric system of units (and several supporting conventions) was adopted partly for just this reason: we do not need to specify each time what we mean by this or that unit.

4. Two approaches to redefining the kilogram

In addition to the intention of resolving the problem of using two versions of SI simultaneously, there is also the explicit wish of replacing the artificial kilogram standard with a natural one. Actually, if such a replacement is done without loss of accuracy, several advantages immediately materialize: there is no need to be concerned about the stability of the standard, there is no need to travel to Paris, etc. The

[2] The mass of the international prototype is equal, by definition, to one kilogram. What this means is that its numerical value is equal to unity and, hence, does not change. Such a definition does not fix the mass of the prototype, i.e., what we call the kilogram. A change in the mass of an object can be observed, since the equations of motion include the derivative of momentum, the products of mass and velocity. The relative variation of mass is observable irrespective of how the unit of mass is defined.

[3] These factors appear in some quantities because the combination e^2/h is known with higher accuracy than the components e and h separately.

suggestion made by Mills et al. [1] is formulated in such a way that the implementation of these advantages may be seen as the main motivation for writing that article. If we deal only with the standard of kilogram, a number of possibilities for solving this problem exist.

Generally speaking, the kilogram can be redefined by fixing the Planck constant h or the Avogadro constant N_A. This can be done either simultaneously with the redefinition of the ampere or independently. Mills et al. [1] tried to demonstrate a neutral attitude on a number of questions and simply exposed the merits and drawbacks of the different versions of the natural definition of the kilogram, leaving the reader with the opportunity to decide for themselves. A logical result of such an approach was the fact that the simultaneous redefining of the ampere was perceived as an opportunity rather than a necessity. The similarity between the redefinition of the kilogram proper and the redefinition of the meter in 1983 is quite natural and does not indicate any preference of the redefining process proposed by Mills et al. [1]. This made their suggestion vulnerable to criticism.

There are advantages to redefining the kilogram and the ampere simultaneously, which may compensate for the loss of accuracy in measuring mass in SI units. When only the kilogram is redefined, these advantages are severely restricted, and the loss of accuracy in measurements of mass becomes an unquestionable drawback. Simultaneous redefinition of the kilogram and the ampere with the goal of transferring to an SI version in which R_K and K_J are fixed can be achieved only by fixing h and e. To redefine the kilogram proper we can also fix N_A; in view of the fact that the accuracy with which the molar Planck constant hN_A is known (see Table 1) is higher than the accuracy with which the stability of the kilogram can be verified, the fixation of h or N_A in order to define the unit of mass will lead to practically identical results. The differences will concern electrical measurements.

The attitude toward the discrepancy in determining the Planck constant by different methods is also very different (see Fig. 1). When only the kilogram is redefined, the situation appears to be such that, instead of a reliable standard with years of its successful use, we arrive at a method that leads to contradictory results. There is the illusion that if we simply do not decide to redefine the kilogram, this discrepancy will amount to an ordinary scientific problem, a problem that has nothing to do with SI units. However, the ampere of SI is determined by the same experiments (experiments on determining h), which means that at present they play a key role in the realization of SI units. The only thing that we can decide is to realization of which unit they are related. What is also important is that the real consequences of this contradiction were and will be extremely limited. Finding the Planck constant is necessary if we want to calibrate a practical unit in terms of SI units (today, the ampere and the volt; after the kilogram and ampere have been redefined, the kilogram). However, in most cases it is enough to know the results in practical units, and no conversion to SI units is needed.

5. The reaction of various committees and commissions to the redefinition of the kilogram

Before the CCU meeting, the suggestion by Mills et al. [1] was examined by the appropriate consultative committees (CCEM, for electricity and magnetism; CCM, for mass and related quantities, and CCQM, on the amount of substance and metrology in chemistry) of CIPM. These committees examined the proposition in the light of redefining only the kilogram and decided it was inappropriate at the moment. Nevertheless, they considered it suitable, if needed, to return to this problem later (in four years) before the next CIPM session.

At roughly the same time, the Commission on Symbols, Units, Nomenclature, Atomic Masses, and Fundamental Constants (SUNAMCO) presented its recommendation to CIPM. Being a commission of the International Union of Pure and Applied Physics (IUPAP), SUNAMCO should (it would seem) express the opinion of physicists rather than

Table 1. Numerical values of the constants mentioned in the article and represented in terms of different units (cf. Ref. [4]) according to the definitions of SI [2], the CODATA values [7], and the recommendations by CIPM [5]; u_r is the relative standard uncertainty.

Constant	Value	Unit	u_r	Source
$m(\mathcal{K})$	1	kg	exact	SI
	$1 - 1.0(1.7) \times 10^{-7}$	$V_{90}^2\ m^{-2}\ \Omega_{90}^{-1}\ s^3$	1.7×10^{-7}	CODATA*
c	299 792 458	$m\ s^{-1}$	exact	SI
μ_0	$4\pi \times 10^{-7}$	$N\ A^{-2}$	exact	SI
	$4\pi \times 10^{-7} \times [1 - 17.4(3.3) \times 10^{-9}]$	$s\ \Omega_{90}\ m^{-1}$	3.3×10^{-9}	CODATA*
e	$1.602\,176\,53(14) \times 10^{-19}$	C	1.7×10^{-7}	CODATA
	$1.602\,176\,49(66) \times 10^{-19}$	C	4.1×10^{-7}	CIPM*
	$1.602\,176\,492\ldots \times 10^{-19}$	$V_{90}\ s^{-1}\ \Omega_{90}^{-1}$	exact	CIPM
h	$6.626\,069\,3(11) \times 10^{-34}$	J s	1.7×10^{-7}	CODATA
	$6.626\,068\,9(38) \times 10^{-34}$	J s	5.7×10^{-7}	CIPM*
	$6.626\ 068\ 854 \times 10^{-34}$	$V_{90}^2\ s^2\ \Omega_{90}^{-1}$	exact	CIPM
R_K	25 812.807 449(86)	Ω	3.3×10^{-9}	CODATA
	25 812.807 0(25)	Ω	1×10^{-7}	CIPM
	25 812.807	Ω_{90}	exact	CIPM
K_J	$483\,597.879(41) \times 10^9$	$Hz\ V^{-1}$	8.5×10^{-8}	CODATA
	$483\,597.9(2) \times 10^9$	$Hz\ V^{-1}$	4×10^{-7}	CIPM
	$483\,597.9 \times 10^9$	$Hz\ V_{90}^{-1}$	exact	CIPM
N_A	$6.022\,141\,5(10) \times 10^{23}$	mol^{-1}	1.7×10^{-7}	CODATA
hN_A	$3.990\,312\,716(27) \times 10^{-10}$	$J\ s\ mol^{-1}$	6.7×10^{-9}	CODATA

* The value was not given in the work cited, but is obtained from it.

metrologists. Actually, this commission constitutes a group of physicists and metrologists. Its recommendation differs substantially from those of the above three commissions (CCEM, CCM, and CCQM). Although the final decision to postpone the redefinition for four years is the same in all commissions, the statement of the problem differs: here, the simultaneous redefinition of the kilogram and the ampere is involved. The key issue is not the accuracy of the new implementation of the kilogram by itself but the need to improve the overall situation, even with a certain reduction in the accuracy of measuring masses in SI units, provided that the accuracy of applying SI units to electrical measurements increases substantially.

Several facts explain such a recommendation. The general position is determined by the composition of the group: since the group includes many metrologists, it is impossible to ignore practical aspects and discuss only general physical aspects of the problem. It is also important that the question of the necessary accuracies and the general extent of precision measurements has not been studied, with the result that opinions on whether the given redefinition would be useful if adopted now have no ground. In any case, being a member of this commission, I noticed no attempts to discuss this problem.

The attitude of the CODATA Task Group on Fundamental Constants is fairly close to that of SUNAMCO. Bearing in mind that the various CIPM commissions have practically blocked the possibility of redefining the kilogram and the ampere by the 2005 decision of CIPM, the group noted that on the whole the redefinition is desirable and must be carried out as soon as possible. The group remarked that the kilogram and the ampere should be redefined simultaneously, and that the two should be redefined by fixing the numerical values of h and e. The question of other units, which will be discussed below, was also raised.

The decision at the CCU meeting, which took place after all the above recommendations were approved, stated that technical prerequisites are needed before the decision on the redefinition can be approved by the CIPM session in 2009. The idea is to ask CIPM to entrust CCU with the task of working out the respective proposition. Bearing in mind that the basic documents on the SI system of units are the object of an international agreement, I would say that such a bureaucratic approach is not very surprising.

6. On redefining the mole and the kelvin

The possibility of redefining the mole and the kelvin was also discussed at the sessions of the CODATA Task Group and CCU of CIPM. The situation here is quite similar to the one that occurred in 1983, when the meter was redefined. The redefinition involves every unit separately and does not affect simultaneously different areas of measurements. In view of the well-known isolation of the corresponding areas of measurements, the proposals concerning such redefinition were discussed on a smaller scale as the redefinition of the kilogram.

Here, I will not consider the technical aspects of such a redefinition, leaving it to specialists of the respective section committees, whose opinion will be decisive in setting the schedule for such a redefinition. I would like to mention, however, the conceptual difference of such redefinitions from the redefinition of the meter. The difference is not concerned with technical aspects, since technically the analogy is complete; instead it involves the possible consequences. As is known, the kelvin and the mole are, generally speaking, not necessary units (e.g., see Ref. [6]). When they emerged and were then traditionally used, the relations between temperature and the average energy per degree of freedom and between the amount of substance and the number of particles (atoms, molecules, etc.) were unclear. However, the subsequent prolonged use of these units is due not so much to tradition as to the fact that direct operations with thermodynamic parameters proved to be, from the standpoint of accuracy, more successful than with the microscopic description of the same objects. For instance, the amount of substance is, actually, nothing more than an unknown number of particles whose mass is known. On the other hand, when speaking about the number of particles, we had in mind a known number of particles with a mass not known exactly. The amount of substance could be characterized by weighing much more accurately than by counting the particles. From the viewpoint of measurements, the number of particles and the amount of substance are at present complementary quantities: both cannot be known simultaneously with absolute accuracy.

Fixing the value of the Avogadro constant would change the physical meaning of the amount of substance and the mole. The idea (see Ref. [8]) is to define the mole in terms of a fixed value of N_A with the kilogram defined independently (say, by fixing the value of h). This means that the amount of substance will be identical to the number of particles. The mole as a term would denote a certain known dimensionless number (equal to the redefined Avogadro number [4]), i.e., would be an analog of, say, the word *million*. Descriptions in terms of amount of substance and number of particles would be identical. Actually, such a redefinition would be the first step in repudiating the mole as a base SI unit and to removing the very concept of the 'amount of substance' from physics textbooks.

A similar situation exists with the concept of temperature. For a long time, the Boltzmann constant was not known very precisely, with the result that the average energy per degree of freedom and the temperature were determined with different accuracy. By fixing the Boltzmann constant k we move from the thermodynamic temperature measured in kelvins to the energy temperature measured in joules.

With this in mind, it is important to note that the fixation of k and N_A, the decision about which will be taken on the basis of the recommendations prepared by the appropriate CIPM consultative committees, will have methodical consequences of great impact.

It should be emphasized that today the concepts of the Avogadro constant and the mole are closely linked to the atomic mass unit. If we were to fix the Avogadro constant and define, on its basis, the kilogram, the relation between the kilogram and the atomic mass unit would change: they would find themselves rigidly linked via the well-known conversion factor defined in terms of the same Avogadro constant. When h and N_A are fixed simultaneously, the relation also changes, but quite differently: the relation between these units of measurement of mass is *a priori unknown*, but *neither* is it described by the Avogadro constant.

[4] We must distinguish between the dimensionless Avogadro number (at present, the number of atoms in 12 grams of carbon-12) and the dimensional Avogadro constant N_A which in a certain sense is equal to unity.

It must also be noted that the terminology related to the mole and the amount of substance is inappropriate for modern physics. The key idea here is that matter consists of atoms. Modern ideas on this subject (concerning the structure of matter) are somewhat different, however. For instance, liquid conductors, obviously, contain ions, while for crystalline bodies we should speak of electrons and the lattice formed by atomic cores. A physicist assumes that the deuteron consists of a proton and a neutron for the simple reason that he or she can deduce a number of properties of the deuteron from the properties of these two nucleons. A chemist assumes that the water molecule consists of hydrogen and oxygen atoms, having in mind that the molecule dissociates into these atoms, which is not the same thing. Changes in the definitions of the mole and the amount of substance may be a convenient way of bringing to order the terminology in this area.

7. The redefinition of SI units and the accuracy of values of fundamental constants

Fixing the values of some fundamental constants enhances the accuracy of the values of the constants as a whole. For instance, fixing the value of the Planck constant automatically improves the accuracy of defining the Avogadro constant, since their product is known more accurately than each of these constants separately. However, one must distinguish between the numerical values (in certain units) of the constants and the constants proper (e.g., see Ref. [6]). It is impossible to improve our knowledge of nature without making additional measurements or calculations. The accuracy of the numerical values is raised at the expense of substituting their content. The uncertainty in the electron mass expressed in kilograms reflects the accuracy with which we are able to compare microscopic masses with the masses of macroscopic objects, such as, say, the electron and a weight. Defining the kilogram in terms of the fixed values of h and N_A will lead to a situation in which the kilogram becomes a microscopic unit. In the first case, measuring in kilograms would be equivalent to measuring in units of frequency, while in the second case, in atomic mass units. Even today the electron mass in these microscopic units is known more accurately than in kilograms. When the redefinition is enforced, the electron mass in kilograms will have no bearing on the comparison of the electron and a weight, and the accuracy of such a comparison will become the accuracy with which the mass of the kilogram prototype is known.

For most constants, the physical meaning of their numerical values changes. Some constants, such as the Avogadro constant, in a certain sense are trivial (they are simply an analog of unity), while the main meaning lies in their numerical values. This is stressed by the fact that in addition to the dimensional Avogadro constant N_A its numerical value $\{N_A\}$ (the dimensionless Avogadro number) is also considered.

How does the meaning of the Avogadro number change from one variant of the SI system to another? Today, $\{N_A\}$ is responsible for the number of particles in an amount of substance with a mass known in macroscopic terms (in kilograms), for example, the effective number of atoms[5] in a bar or weight. If we redefine the kilogram in microscopic terms by fixing h, the accuracy of the Avogadro number enhances, but its meaning changes. We will now be concerned not with how many atoms are contained in a weight but how many electron – positron pairs can be produced by a known number of photons with a known frequency (most such analogies are meaningless from the experimenter's viewpoint since we must also check that, for instance, the electron – positron pairs have no kinetic energy, while saying that the rest energy of a number of atoms is equal to the total photon energy does not clarify matters too much). If the kilogram is redefined by fixing $\{N_A\}$, the meaning of this constant also changes and becomes trivial, since mass in kilograms will correspond to mass expressed in atomic units and, although the formal definition of the Avogadro constant will retain its meaning, it will become a tautologous statement. If we redefine the mole by fixing $\{N_A\}$, the physical meaning of this constant changes as well. The Avogadro number will then correspond to a known, by definition, number of particles in an amount of substance of unknown mass. Here, the accuracy of determining the effective number of particles in an amount of substance whose mass is known in macroscopic terms, say, in a carbon bar whose mass is equal to that of the kilogram prototype, remains the same. Only the relationship between this very real number and the abstract Avogadro number changes.

If, as we see, nothing 'actually' is made more precise, can we assume that the redefinition of units provides a matter of advantages related to fundamental constants? The answer is yes. Not only do the values of the constants reflect our knowledge of nature, they also serve as a sort of reference data which are important either due to their convenience or in view of tradition. For instance, it is common practice to express the masses of elementary particles, nuclei, and atoms in electron-volts. In the modern version of SI, many of these quantities are known in atomic mass units with a much higher accuracy than in other units. Another example is the widely accepted practice of using electron-volts when measuring the energies of X-ray and gamma transitions, rather than the frequencies of the transitions in hertz (or the wave numbers in reciprocal meters), which are known, as a rule, with a higher accuracy. The problem with accuracy emerges because usually one deals not directly with the measured quantities but with their derived quantities. How is one to treat such quantities for adequately representing the results? There are three main approaches here: we can depart from tradition and use only those units in terms of which the result is expressed most accurately; we can follow the tradition but explicitly indicate the uncertainty of conversion to electron-volts and, separately, the error of the measurements proper; or we can introduce nominal electron-volts by using, say, the volt-1990 unit. Every one of these approaches requires making an effort and leads to certain inconveniences. However, leaving the situation as it is now, we inevitably lose accuracy. The numerical values of the constants in this case act as conversion factors from one system of units to another. If the accuracy of these values enhances (even at the expense of changing their physical meaning), a useful effect is accomplished: the results expressed in electron-volts, which are used universally, acquire sufficiently high accuracy. Thus, we can say that the redefinitions of the kilogram, the ampere, and, possibly, other units substantially simplify the employment of a broad spectrum of reference data and conversion factors, among which fundamental constants and their numerical

[5] As noted earlier, solids do not consist of atoms, and so we can speak only of the effective number of atoms.

values occupy a special place. As noted earlier, the question of selecting the proper system of units is largely a question of convenience in describing the measurement results.

8. Is it obligatory to use SI units in physics?

In addition to various aspects of defining the base units of SI in terms of fundamental physical constants, CCU also discussed the new edition of the SI brochure,[6] which should replace Ref. [2]. One indisputably positive change that should be emphasized here is the mention in the text that some units differing from SI units are (and will be) widely used and that scientists must be allowed to use units that they consider appropriate in solving their problems. The first statement was included in the previous edition of the brochure (see Ref. [2]) in a weaker form, while the second appeared only now.

9. The SI system and physicists

Since in these notes we are dealing with physical units, it would be advisable to specify the meaning of the word 'physics' and to see how the opinion of physicists is represented in CCU and other similar bodies. I believe that CCU does not have a clear understanding of what physics is. The nature of the discussions and some of the statements show that the topic is mostly referred to educational physics rather than to research physics. Clearly, different areas of phenomena are represented in teaching and research in different proportions. While SI plays an important role in school and college physics courses, the role of some non-SI units is great in research. One reason for this is that the above-mentioned physics courses are intended to describe a broad spectrum of phenomena, while most researchers deal with narrow areas, in which the use of certain non-SI units is very convenient.

However, the opinion of teachers is not represented in CCU or SUNAMCO, although in some discussions topics related to education do appear. While some of the participants of the discussions held at CCU do have a background of teaching at universities, not one has taught physics at school. The viewpoint of professional instructors and authors of popular physics textbooks is not represented at the discussions. The opinion of researchers should, at least theoretically, be represented at the SUNAMCO Commission of the Union of Physicists. This commission is formed mainly by specialists in mass spectroscopy, fundamental constants, standards, and precision measurements as a whole. Its participants are, unquestionably, experts in the area of physical metrology. However, the general questions concerning the system of units cannot be reduced to metrology, since they have important methodical and conceptual implications. Building a system of units is a problem of physics as a whole and embraces the interests of all physicists. However, professional researchers in physics with a broad outlook have regretfully limited knowledge in the field of metrology. To build an advantageous system of units (here we are speaking of a version of the SI system), a dialog between physical metrologists and the majority of physicists, who are not metrologists, is needed. There is only one professional group of physicists interested in such problems, the Task Group on Base Units and Physical Constants of the French Academy of Sciences. The SUNAMCO Commission and similar groups successfully complement each other, and it would be advisable to create such a group in Russia. The importance of these groups is growing since we expect substantial changes to take place in the International System of Units (SI), and physicists must have the opportunity to express their views on the subject and to voice their opinion at the International Committee on Weights and Measures (CIPM), which will make the decision.

10. The future of SI

The nature of the discussions held at CCU suggests that most likely the redefinition of the kilogram and the ampere will take place four years from now. The new definitions will be based on the fixed values of h and e. Of course, judging by the discussions held in various task groups and committees, this is not so obvious. And yet, having taken a contrary position, people often ignore practical evidence. This fact will inevitably play an important role in the process of redefinition. Allowing for the requirements related to electrical measurements, we can say that freedom of choice in solving the problem of redefining the kilogram and the ampere in terms of fundamental constants is extremely limited.

The fate of the kelvin and the mole is not so clear because the issue was not discussed so intensively. But it is obvious that their redefinition is only a question of time, so that if not in four years then, most probably, in eight or, at the most, twelve years they will be redefined.

This will not stop the process of transforming the SI system. Not very soon, but in the foreseeable future, a new definition of the second could be on the agenda. After several decades of the domination of the radio-frequency hyperfine transition in caesium atoms, many other alternative clocks have appeared for the first time. They, of course, are still inferior to the caesium clock, but progress is very rapid in this field.

The status of the candela may also change. The role played by measurements of 'subjective' quantities related to humans, ecology, etc. is growing in modern society very fast, and this requires adequate metrological substantiation, of course. Today, the approach to such units is, in a certain sense, of a random nature, so that, for instance, while the candela (a unit of subjective perception of the intensity of a source of light) is one of the base SI units, the sievert (the unit of subjective perception of a radiation dose) is a derived unit. However, the two are very similar. I hope that within a systematic approach to the problem it will be finally acknowledged that such quantities do not really belong to physics, so that their units, including the candela, must be treated differently from the units of real physical quantities.

What, probably, will remain from the modern definitions of the base SI units will be the fixed value of the speed of light in vacuum. Adopted in 1983, this fixed value was the first step, so to say, in solving the problem of representing the units of the base physical quantities in terms of fundamental physical constants. The next important step is likely to be taken in four years. This will be the redefinition of the kilogram and the ampere, which will lift the last artifact from the definitions of units of physical quantities.

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[6] See http://www1.bipm.org/en/si_brochure/.

11. Appendix. Abbreviations and the full names of the various international bodies mentioned in the article

BIPM, the French abbreviation of Bureau International des Poids et Mesures, or the International Bureau on Weights and Measures;

CCEM, Consultative Committee for Electricity and Magnetism;

CCM, Consultative Committee for Mass and Related Quantities;

CCQM, Consultative Committee on the Amount of Substance and Metrology in Chemistry;

CCU, Consultative Committee for Units of CIPM;

CIPM, the French abbreviation of Comité International des Poids et Mesures, or International Committee on Weights and Measures;

CODATA, Committee on Data for Science and Technology of the International Council of Science (ICSU);

CODATA Task Group on Fundamental Constants;

GCWM, General Conference on Weights and Measures;

IUPAP, International Union of Pure and Applied Physics;

IUPAP Commission on Symbols, Units, Nomenclature, Atomic Masses, and Fundamental Constants (SUNAMCO).

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