**METROLOGY AND MEASUREMENT SYSTEMS**

**Review Paper**

# THE QUANTUM SI – TOWARDS THE NEW SYSTEM OF UNITS

## Waldemar Nawrocki

*Poznan University of Technology, Faculty of Electronics and Telecommunications, Polanka 3, 60-965 Poznan, Poland*
*(✉ nawrocki@et.put.poznan.pl, +48  61 665 3888)*

**Abstract**

The possibility or even necessity of revising definitions of some of the base units of the present SI has been discussed over the past 15 years. The  last General Conference of Weights and Measures (2007) recommended to redefine the kilogram, the ampere, the kelvin, and the mole using fixed values of the fundamental constants by the time of the next General Conference in 2011. This paper is a review of proposals of new definitions of units of mentioned quantities and arguments voting for particular variants of definitions. Most relevant papers for this review  have been published by *Metrologia*, the international journal appointed at the BIPM, and many other useful pieces of  information are available on www pages of the BIPM. The author notes that not only new definitions have been discussed but as well as the set of the base units of the SI. It means a replacement of the ampere by the volt or the kelvin by the joule. Decisions concerning new definitions are not made and the discussions are still open.

Keywords: SI system, base units, quantum standards.

## 1. Introduction

The present International System of Units (SI) is 50 years old. The SI was accepted by the 11th General Conference on Weights and Measures (CGPM) in 1960 [1]. At its starting-point, the system of units contained 6 base units (valid from 1954), two supplementary units (radian and steradian) and derived units. In 1971 the 14th CGPM increased the number of base units of the SI system to 7 by adding the mole – the unit for amount of substance. Then, from 1971, the base units of the SI system are: the metre, the kilogram, the second, the ampere, the kelvin, the candela and the mole.

Base units play very important role in a measurement system [2, 3]. The accuracy of representation of derived units is based on the accuracy of base units representation. The base units are sufficient to define the derived units of geometric, mechanical, electric, thermal, magnetic, light, and acoustic quantities as well as the units of ionizing radiation (22 derived units with their names and symbols are listed in [1]). It can be easily understood that the efforts of metrological institutions tend to represent base units with a minimal uncertainty, what always generates costs. Among 7 base units in the present SI system only 3 units are independent: the kilogram, the second, and the kelvin. Four remaining units: the metre, the ampere, the candela and the mole are derived from kilogram and second (see Fig. 1).

An advantage of a system of measures are mutual relations between of quantities. In a system the units of particular physical quantities may be represented and defined by units of other quantities. *E.g.* this way the ampere, the measurement unit of electric current, may be

defined by measuring force and length. The only base unit of the SI system with no link to other base units is the kelvin.

The possibility or even necessity of revising definitions of some of the base units of the present SI has been discussed over the past 15 years. The discussions concern redefinition of the four base units: the kilogram, the ampere, the kelvin and the mole. Especially, there is a necessity to redefine the kilogram. At present only the kilogram is defined in terms of a material artifact – the international prototype of the kilogram. Taking advantage of recent achievements of physical science in metrology made possible the build of quantum standards of units which use fundamental physical constants or atomic constants.
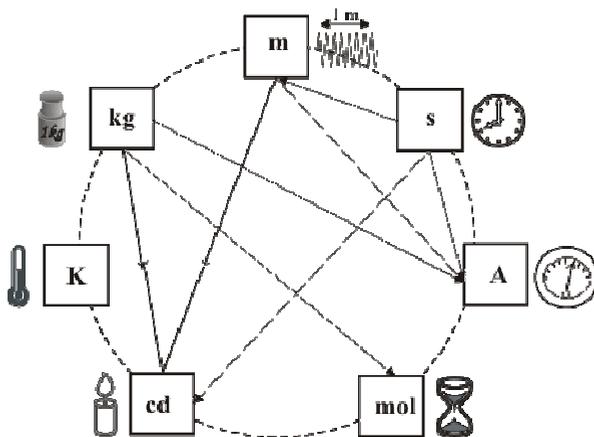


Fig. 1. SI base units.

A definition of the metre is based at present on the constant $c_0$ – the velocity of light in vacuum. Definitions of the volt and the ohm use the Planck constant $h$ and the elementary electric charge $e$. Quantum standards of the volt and of the ohm operate using the quantum phenomena: the Josephson effect and the quantum Hall effect, respectively.

Composition of the set of the base units in the SI is discussed as well. Proposals were published to replace the ampere by the volt and the kelvin by the joule. The proposal of replacing the kelvin, unit of temperature, by the joule, unit of energy was presented in papers [4, 5]. Numerous arguments are presented in favor of such change. The set of base units should comprise the measurement units of physical quantities, which are the most important for human beings, *e.g.* applied in trade. Therefore, among base units there are the measurement units for length (metre), mass (kilogram), and time (second). Because energy is also the subject of common trade exchange on a large scale, the measurement unit of energy (joule) and the accuracy of its standardization have a great effect on trading and commercial activity. Energy is perhaps the most universal physical quantity in nature. One of the formulations of the first thermodynamics principle reads: "The quantity of energy in the universe is always constant". Different forms of energy: mechanical energy or work, thermal energy, electric energy and nuclear energy, enable mutual comparisons of the standards of mechanical quantities, thermal quantity standards, electric quantity standards and mass standards, as well as comparing them to the standard of energy measurement unit. As far as a limit resolution of measurements is concerned, we usually have to take into consideration energy changes affecting (influencing) the measuring sensor. Energy is one of four physical quantities occurring in inequalities describing quantum limits of measurement resolution, according to the Heisenberg uncertainty principle. Three others quantities are: time, length

(for position) and momentum. So far the idea of replacing the kelvin by the joule has not been supported by many metrologists. Replacing the ampere by the volt is discussed in paragraph 4.2.

Redefinitions of the SI base units have been discussed at the 94th Meeting of the International Committee for Weights and Measures (2005) and during the 23th CGPM in 2007 (the last General Conference). In its 12th Resolution "On the possible redefinition of certain base units of the International System of Units" the 23th General Conference considered [1]:

− "that, for many years National Metrology Institutes as well as the International Bureau of Weights and Measures (BIPM) have made considerable efforts to advance and improve the SI by extending the frontiers of metrology so that the SI base units could be defined in terms of the invariants of nature – the fundamental physical constants,
− that, of the seven base units of the SI, only the kilogram is still defined in terms of a material artifact – the international prototype of the kilogram (2nd CGPM, 1889, 3rd CGPM, 1901) and that the definitions of the ampere, mole and candela depend on the kilogram, …,
− the many advances, made in recent years, in experiments which relate the mass of the international prototype to the Planck constant $h$ or the Avogadro constant $N_A$, …,
− initiatives to determine the value of a number of relevant fundamental constants, including work to redetermine the Boltzmann constant $k_B$,
− that as a result of recent advances, there are significant implications for, and potential benefits from, redefinitions of the kilogram, the ampere, the kelvin and the mole …".

Following the above arguments, the 23th General Conference recommended in the 12th resolution:

− "pursue the relevant experiments so that the International Committee can come to a view on whether it may be possible to redefine the kilogram, the ampere, the kelvin, and the mole using fixed values of the fundamental constants at the time of the 24th General Conference (2011),
− should, together with the International Committee, its Consultative Committees, and appropriate working groups, work on practical ways of realizing any new definition based on fixed values of the fundamental constants, prepare a *mise en pratique* for each of them, and consider the most appropriate way of explaining the new definitions to users ...".

## 2. Units of measure based on fundamental physical constants

Fundamental physical constants are universal and invariant. Therefore they are good references for units of system of measure. If we decided to create a system of units based on fundamental constants, the problems to be solved are: which of many physical constants should be taken for such system and how should they be redefined. Almost 180 years ago, in 1832, in his dissertation "Die erdmagnetische Kraft auf ein absolutes Maß zurückgeführt" Carl Gauss proposed a coherent measurement system of units containing the units of measurement for: length, mass, and time. Magnetic properties of the Earth were used for defining the units in this system. Some years after that electric quantities were included into the system proposed by Gauss and Weber. A similar proposal of using physical constants for defining measurement units was made by J. C. Maxwell. Richard Feynman stated that in quantum electrodynamics there are only two physical constants in principle, and a major part of other constants should result from those two [6]. Both constants are electron parameters: the elementary charge $e$ and the rest mass $m_e$ of the electron. Now we come back to these ideas.

The simple system of units based on fundamental constants was proposed by Mills *et al* [7]. "The International System of Units, the SI, is the system of units scaled so that:

1. ground state hyperfine splitting transition frequency of the caesium 133 atom
   $\Delta\nu\,(^{133}\mathrm{Cs})_{\mathrm{hfs}}$ is 9 192 631 770 hertz,
2. speed of light in vacuum $c_0$ is 299 792 458 metres per second,
3. Planck constant $h$ is $6.626\ 0693 \times 10^{-34}$ joule second,
4. elementary charge $e$ is $1.602\ 176\ 53 \times 10^{-19}$ coulomb,
5. Boltzmann constant $k_B$ is $1.380\ 6505 \times 10^{-23}$ joules per kelvin,
6. Avogadro constant $N_A$ is $6.022\ 1415 \times 10^{23}$ per mole,
7. spectral luminous efficacy of monochromatic radiation of frequency $540 \times 10^{12}$ hertz
   $K(\lambda_{555})$ is 683 lumens per watt.

Accompanying this definition of the SI would be a list of representative units, together with a representative list of the quantities whose values could be expressed in those units". The list of units includes the metre, the kilogram, the second, the ampere, the kelvin, the mole and the candela as well as the current 22 derived units (from the present SI). One can note that the proposed new SI [7] is rather a set of physical constants, not a system of units. In the proposed new SI the units are not divided between base units and derived units. "All units are on an equal footing" [7].

In the seven definitions presented above physical constants have fixed values. The values for some fundamental constants, necessary for new definitions of the SI units, must be exactly known. At present only the speed of light in vacuum $c_0$ is fixed as the fundamental constant, $c_0 = 299\ 792\ 458\ \mathrm{ms}^{-1}$. The other constants which are not fundamental, namely the spectral luminous efficacy of radiation, $K(\lambda_{555}) = 540 \times 10^{12}$ Hz, and the transition frequency of caesium 133, $\Delta\nu\,(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9\ 192\ 631\ 770$ Hz, are fixed as well. The values of four remaining fundamental constants must be fixed for new definitions of the SI units. This requirement concerns the Planck constant $h$, the elementary charge $e$, the Boltzmann constant $k_B$ and the Avogadro constant $N_A$. The set of the fixed constants is not fixed, it can be altered. For example, the Planck constant $h$ and the elementary charge $e$ could be replaced by the Josephson constant $K_J$ and of the von Klitzing constant $R_K$ (1) in the set of fixed constants. The two latter constants appear in quantum effects and are measured very precisely.

$$K_J = 2e/h, \quad R_K = h/e^2$$

$$e = 2/(K_J \times R_K), \qquad h = 2(e/K_J) \tag{1}$$

The values to be fixed can be taken from the expected 2010 CODATA set of recommended values (CODATA, the Committee on Data for Science and Technology). The values of fundamental physical constants (useful for the SI) presented in the latest edition of the CODATA set (2006) are listed below [8]. They differ from the CODATA values from the previous 2002 edition.

− $h = 6.626\ 068\ 96 \times 10^{-34}$ Js, the relative standard uncertainty $u_r \geq 5.0 \times 10^{-8}$,
− $e = 1.602\ 176\ 487 \times 10^{-19}$ C, $u_r \geq 2.5 \times 10^{-8}$,
− $k_B = 1.380\ 6504 \times 10^{-23}$ JK$^{-1}$, $u_r \geq 1.7 \times 10^{-6}$,
− $N_A = 6.022\ 141\ 79 \times 10^{23}$ mol$^{-1}$, $u_r \geq 5.0 \times 10^{-8}$,
− $m_e = 9.1109\ 382\ 15 \times 10^{-31}$ kg, $u_r \geq 5.0 \times 10^{-8}$.

A relative standard uncertainty $u_r$ of measurements of these five fundamental constants has been improved continuously, *e.g.* in 2002 there were the following values: $u_r \geq 1.7 \times 10^{-7}$ for the $h$, $u_r \geq 8.5 \times 10^{-8}$ for the $e$, $u_r \geq 1.8 \times 10^{-6}$ for the $k_B$, $u_r \geq 1.7 \times 10^{-7}$ for the mole, and $u_r \geq 8 \times 10^{-8}$ for the electron mass $m_e$.

Two physical constants with fixed values in the present SI, the magnetic permeability in vacuum $\mu_0 = 4\pi \times 10^{-7}$ NA$^{-2}$ and the molar mass of carbon $^{12}$C, $M(^{12}\mathrm{C}) = 12$ g/mol, will be no more fixed and no more known exactly. They can be simply measured with uncertainty.
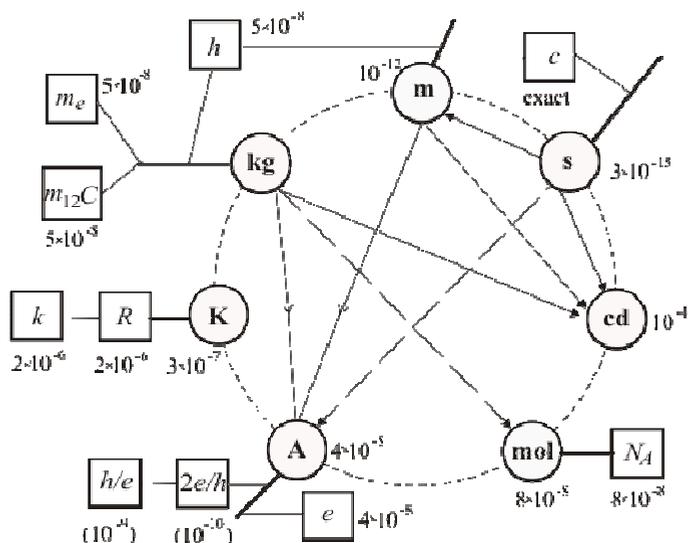
Fig. 2. Linking SI base units to fundamental constants [3] (values of relative standard uncertainty according the 2006 CODATA set [8]).

At present there are more constants-candidates for new definitions of units than necessary. *E.g.* the kilogram can be defined using either the Planck constant *h* or the Avogadro constant $N_A$, the kelvin can be defined either by the Boltzmann constant $k_B$ or by the molar gas constant *R* – see Fig. 2.

## 3. The kilogram

The kilogram is still defined in terms of a material artifact. The definition in the SI system reads as follows: "The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram". The international prototype of the kilogram (IPK) is a cylinder with a diameter of 39 mm, it is made of an alloy of platinum 90% and iridium 10%. The IPK is kept at the International Bureau of Weights and Measures (BIPM) at Sèvres. Almost one hundred Pt-Ir copies of the international prototype of kilogram have been made up today. Six of these are called official copies of the IPK and kept together with the IPK at the BIPM. Eight other Pt-Ir artifacts are used by the BIPM for calibration tasks. The remaining eighty Pt-Ir copies of the international prototype of the kilogram have been distributed to national laboratories all over the world. Copy No 51 is used by the Central Office of Measures (GUM) – the national laboratory of metrology in Poland.

The definition of the kilogram is important not only for the unit of mass but for three other base units, namely the ampere, the mole, and the candela as well. Thus, any uncertainty inherent in the definition of the kilogram is transferred on these three units.

There are several difficulties with the present standard of the kilogram. The IPK (standard) can be used in Sèvres only. The IPK can be damaged or even destroyed. The IPK collects contaminants from air, approaching 1 µg per year in mass [9]. Therefore, the International Committee for Weights and Measures (CIPM) declared that, the reference mass of the international prototype of the kilogram is that immediately after cleaning and washing it by a specified method. The described cleaning, washing and drying operations take a time of about 3 weeks [1]. However, the most important disadvantage of the international prototype is a long-time drift of its mass. The international prototype of the kilogram is in service since

1889. The second (1939–1953) and third (1989–1992) periodic verifications of national prototypes of the kilogram have shown that the mass of the international prototype changed, with respect to the ensemble copies, by  –50 µg after 100 years. It means a relative change of $5 \times 10^{-8}$ per 100 years. The reason of this effect is unknown. The changes of the masses of Pt-Ir artifacts with respect to fundamental constants has been obvious after the third verification period. Thus, the definition and the standard of mass must be altered. After many proposals and discussions a possible new definition of the kilogram will be related to one of the two fundamental constants, namely: the Planck constant $h$ or the Avogadro constant $N_A$.

In 2007 the Consultative Committee for Mass and Related Quantities at the CIPM  (10th meeting of CCM) discussed new definitions of the kilogram and the mole. There were 7 new definitions of the kilogram, each of them relates to a physical constant (to one or many). All seven presented definitions have been still discussed.

1.  The kilogram is the mass of a body whose Compton frequency is $1.356392\ldots \times 10^{50}$ hertz exactly [10].
2.  The kilogram is the mass of a body whose de Broglie-Compton frequency is equal to exactly $[(299\ 792\ 458^2/(6.626\ 0693) \times 10^{-34})]$ hertz [7].
3.  The kilogram is the mass of a body whose equivalent energy is equal to that of a number of photons whose frequencies sum to exactly $[(299\ 792\ 458^2/(66\ 260\ 693)] \times 10^{41}$ hertz [7].
4.  The kilogram, unit of mass, is such that the Planck constant is exactly $h = 6.626\ 0693 \times 10^{-34}$ Js [7].
5.  The kilogram is $(6.022\ 1415 \times 10^{23}/0.012)$ times the rest mass of the $^{12}$C atom in the ground state [11].
6.  The kilogram is $(6.022\ 1415 \times 10^{23}/0.012)$ times the rest mass of a particle whose creation energy equals that of a photon whose frequency is:
    $[0.012/(6.022\ 1415 \times 10^{23}) \times 299\ 792\ 458^2/66\ 260\ 693 \times 10^{-34})]$ hertz [11].
7.  The kilogram is $1.097\ 769\ 24 \times 10^{30}$ times the rest mass of the electron [12].

The definitions (1–3) use formulas of quantum mechanics and two fundamental constants: $h$ and $c_0$. The definition (4) is very simple but its realization is very far from a practical standard. Physical interpretation of these definitions (1–4) is difficult. At the 10th CCM meeting (2007) E. Williams presented the following explanation of the definition (4): "The kilogram is the mass of $6.022\ 1415 \times 10^{26}$ idealized atoms, each of these atoms having the mass such that the Planck constant, the most important constant in quantum mechanics, has the specified value of $6.626\ 0693 \times 10^{-34}$ Js" [13]. This explanation is little helpful for understanding of this definition.

The Compton wavelength $\lambda_{C,e}$ and the Compton frequency $\nu_{C,e}$ of the electron, mentioned in the definitions (1, 2), are given by formulas (2) and (3).

$$\lambda_{C,e} = h/m_e\,c_0, \tag{2}$$

$$\nu_{C,e} = c_0\,/\lambda_{C,e} = c_0{}^2 m_e/h. \tag{3}$$

Should we put a mass of 1 kg instead of the electron mass into the formula (3), we obtain the Campton frequency of $\nu_C$ (1 kg) $= c_0{}^2 m/h \approx 1.356 \times 10^{50}$ Hz which appears in the first definition. Such extremely high frequency of $10^{50}$ Hz has no practical meaning. The definitions (5–7) are related either to the mass of the carbon atom (5, 6) and the Avogadro constant or to the mass of the electron (7). Each of the definitions (5–7) describes the kilogram as a mass $n$-times larger than the mass of a particle. A standard mass defined this way could be better understood than the mass expressed in frequency units.

The CCM (2007) considered all these seven definitions of the kilogram. Arguments for one from the definitions (5–7) are as follows. "The kilogram mass is a classical, macroscopic

quantity, whereas Compton frequency and Planck constant describe quantum mechanical effects. How the mass of a macroscopic body (1kg) is related to quantum mechanics is not clarified and experimentally proved" [12].

## 4. New definitions of the ampere, kelvin and mole

### 4.1. *The ampere*

In the present SI: "The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ newton per metre of length ". The Consultative Committee for Electricity and Magnetism (CCEM) at the CIPM discussed redefinitions of the ampere in 2007 and 2009 [14]. The recommendation E1 (2007) of the CCEM, supported by the meeting of the CCEM in 2009, reads:

1. The ampere is the electrical current equivalent to the flow of exactly
    $1/(1.602\ 176\ 53 \times 10^{-19})$ elementary charges per second.

The very similar definition was proposed by Mills et al [7] in 2006. However the second definition of the ampere describes the flow of positive charges (protons).

2. The ampere is the electric current in the direction of the flow of exactly
    $1/(1.602\ 176\ 53 \times 10^{-19})$ elementary charges per second.

The first definition is so far the proposal from the Consultative Committee for Electrical measurements (CCEM). The second definition reflects the opinion of the Consultative Committee for Units (I. Mills is the chairman of the CCU). The CCEM considered also the question what quantity should represent all electrical quantities in the set of base units of the SI? It was not obvious that the ampere will be still the base unit. There are two other possibilities: the volt and the ohm. It seems that either the volt or the ohm could be better base units than the ampere because volt standards and ohm standards have been used since 20 years in metrology. Assuming that the values of *h* and *e* are fixed (such proposal is generally accepted), so the two other physical constants, then Josephson constant $K_J$ and the von Klitzing constant $R_K$, will be known exactly. A definition of the volt, an alternative base unit, can read [12] **:**

3. The volt is equal to the difference between two electrical potentials within which the energy of a pair of electrons equals that of photons whose frequency is $4.835\ 978\ 79 \times 10^{14}$ Hz.

In a Josephson voltage standard the device is a matrix with *n* Josephson junctions. The standard`s voltage *V* depends on a radiation frequency *ν*, which can be measured with a relative standard uncertainty better than $10^{-12}$, and the Josephson constant $K_J$ (4). The Josephson voltage standards are installed in hundreds laboratories all over the world.

$$V = n \times k \times (h/2e) \times \nu = n \times k \times K_J^{-1} \times \nu = n \times k \times [1/(483.5\ 978\ 79 \times 10^{12}\ \text{Hz})] \times \nu, \quad (4)$$

where *V* – the voltage of a Josephson voltage standard, *n* – the number of Josephson junctions in a standard`s matrix, *k* – integer, the step on a voltage-current characteristic of Josephson junction, *ν* – the radiation frequency acting on Josephson junctions.

The ohm is realized by a quantum standard using the quantum Hall effect (QHE). The resistance $R_H$, produced by the QHE standard, depends only on the $R_K$ (5).

$$R_H = (h/e^2)/i = R_K/i, \quad (5)$$

where $R_H$ – the resistance of a QHE standard, $R_K$ – the von Klitzing constant, *i* – integer, the step on the resistance-magnetic inductance characteristic of the QHE sample.

The recommendation E1 (2007) of the CCEM reads "that if the concept of base units is retained then the ampere be kept as a base unit for the purposes of historical continuity and SI dimensional analysis although there is no preferential order of traceability within electrical units" [14]. Eventually the CCEM proposes to leave the ampere in the set of base units and to redefine it.

### 4.2. The kelvin

In the present SI "The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water". Proposals of a new definition of the kelvin were discussed during International Symposium on Temperature Measurements in 2007 and after that published in [15, 16]. The paper [15] has 13 authors from 13 metrology institutions. The authors are members of the Task Group for SI (TG-SI) of the Consultative Committee of Thermometry at the CIPM. The papers [15, 16] describe results of discussions on the new definition. All four new definitions of the kelvin use the Boltzmann constant, no definition is related to the molar gas constant $R = 8.314\ 472$ J/mol$^{-1}$K$^{-1}$ (the latter is possible, see Fig. 2).

The kelvin is the change of thermodynamic temperature $T$ that results in a change of thermal energy $k_B T$ by exactly $1.380\ 65XX \times 10^{-23}$ joule, where $k_B$ is the Boltzmann constant.

1. The kelvin is the change of thermodynamic temperature at which the mean translation kinetic energy of atoms in an ideal gas at equilibrium is exactly $(3/2) \times 1.380\ 65XX \times 10^{-23}$ joule.

2. The kelvin is the change of thermodynamic temperature at which particles have an average energy of exactly $(1/2) \times 1.38\ 65XX \times 10^{-23}$ joule per accessible degree of freedom.

3. The kelvin, unit of thermodynamic temperature, is such that the Boltzmann constant is exactly $1.380\ 65XX \times 10^{-23}$ joule per kelvin.

The XX in the above definitions are the appropriate digits of the Boltzmann constant, according to the current CODATA set. What definition will be recommended? "… the TG-SI is recommending the explicit-constant definition (4) because it is sufficiently wide to accommodate future developments and does not favor any special primary thermometer for realizing the kelvin. Should the CCU (Consultative Committee for Units at the CIPM) decide to adopt explicit-unit definitions for the kilogram, the ampere, and the mole, then the second option of the TG-SI would be the formulation (1) for the kelvin in order to be in line with the other new definitions" [15].

However Kilinin and Kononogov [17] see that the new definition of the kelvin using the Boltzmann constant "is not advisable in view of the present-day level of accuracy and reliability of determination of the value of Boltzmann constant".

The new defined kelvin can be more useful for measurements of thermal properties of materials in nanotechnology, see [18].

### 4.3. The mole

An amount of substance (system) is specially important for chemistry. For analyses of chemical processes and reactions being made by chemists, number rations of particles are necessary. Thus the mole, the unit of amount of substance, should be defined without using a unit of the mass. The definition in the present SI reads: „The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. When the mole is used, elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles". At the 10th meeting (2007) the CCM proposed the following new definition of the mole.

1.  The mole is the unit of amount of substance. It is equal to $6.022\ 1415 \times 10^{23}$ mol$^{-1}$ specified identical entities. The entities may be atoms, ions, molecules or other particles [10].

    The definition of the mole proposed in the paper [7] is similar to the previous one. In the definition (2) authors described the particles as "elementary entities" instead of "identical entities" what is in the definition (1).

2.  The mole is the amount of substance of a system that contains exactly $6.022\ 1415 \times 10^{23}$ mol$^{-1}$ specified elementary entities, which may be atoms, molecules, ions, electrons, other particles or specified groups of such particles [7].

    According to the new definitions the amount of substance $n$ does not refer any longer to the unit of mass. The amount of substance can be described by a formula (5).

$$n = (\text{number of molecules in a sample}) / 6.022\ 1415 \times 10^{23}. \qquad (5)$$

Leonard published some comments and critical remarks concerning the definitions of the mole presented above [19, 20]. He introduced his remarks assuming the total amount of substance $n(S)$ and the corresponding number of the entities $N(S)$. The number-specific amount of substance is $n(S)/N(S)$. He has proposed "using the name entity (plural, entities) and symbol ent for this fundamental physical invariant and formally adopting it as an atomic-scale unit in use with SI..." [19]. Because the proposed new unit, entity, is reciprocally related to the Avogadro constant $N_A$, the amount-specific number of entities, $N_A = N(S)/n(S) = \text{ent}^{-1}$, this proposal has been not accepted by physicists. The Leonard`s comment reads: "The proposals independently redefining the mole (by fixing the Avogadro number, $A_N$) and the kilogram (by fixing the Planck constant) while keeping the $^{12}$C-based definition of an atomic mass unit, the dalton (Da), violate the fundamental compatibility condition stemming from the mole concept. With the mole and kilogram defined independently, if $A_N$ has an exact value, the dalton should be determined by the compatibility condition, Da = $(10^{-3}/A_N)$ kg, exactly. " The correction factor, proposed in [7], for fulfilling the condition for the present definition of the dalton, Da = $m_a$ ($^{12}$C)/12 "create a degree of complexity that is completely unwarranted, ...", where $m_a$ ($^{12}$C) is the atomic mass of carbon $^{12}$C) [20].

## 5. The discussion

It this paper proposals for new definitions of the base units of the SI system are presented. Each new definition of the base unit is related to one or many physical constants. The newly defined units are universal and invariant like the fundamental physical constants used for defining them.

However the new definitions of the base units are more sophisticated and much more difficult to understand than old definitions. They can be difficult not only for the public and students but for technical staff as well. In many cases, for the new definition of a unit there is no link to a practical standard of the unit. Laboratories of metrology will use "old standards" for the new defined units. For the kilogram it is the watt balance set (it may be a sphere made of the isotope $^{28}$Si in form of a single crystal as well [9]), for the ampere there are the Josephson standard of the volt and the QHE standard of the ohm, and for the kelvin there is The International Temperature Scale of 1990. Some laboratories have established a set-up with the watt balance[21]. Even more results with the watt balance set-up were recently published by NIST and NPL. Unfortunately these results disagree by more than their combined standard uncertainties so far [21].

It is a pity that from many consultative committees at the CIPM only the CCT has indicated its preference at the list of proposals for a new definition of the kelvin. Other

committees have not finished their task: to propose one new definition for one base unit. We can note what kind of arguments were considered at solving the problem of a set of the base units (ampere or volt?). The ampere won "for the purposes of historical continuity" [14].

Cabiati and Bich made some remarks on the proposed quantum SI [22]. "Should the explicit-constant definitions be adopted, the lack of wording could be compensated by moving the focus from SI units to SI quantities, whose definitions might be conveniently refined". The new SI gives "opportunities offered... by reference quantities different from fundamental constants. ... such opportunities completely met within the individual metrological system of every quantity, with little implication for the general structure of the SI..." [22].

We can hope that the new definitions for the base units will be accepted by a community of metrology.

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