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THE PROPOSED NEW SI: CONSEQUENCES FOR MASS METROLOGY

Roman Schwartz, Michael Borys

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

Abstract: At its 24th meeting in October 2011 the General Conference on Weights and Measures (CGPM) adopted a Resolution on the possible future revision of the International System of Units (SI). This paper provides an overview of the proposed changes to the SI, the focus being on the proposed redefinition of the kilogram and possible consequences for mass metrology.

Keywords: New SI, redefinition, kilogram, mass.

1. INTRODUCTION

Of the seven base units of the SI, only the kilogram is still defined in terms of a material artefact, namely the international prototype of the kilogram (IPK) kept at the BIPM [1]. Since the third verification of national prototypes of the kilogram (NPK) against the IPK in the period 1989 to 1991 the stability of the IPK has been put into question, because the results of comparisons between the NPKs and the IPK show some divergence with time, the relative mass changes being in the order of 50 µg during a period of about 100 years. Although the mass of the IPK is certainly not stable, neither could its drift yet be determined absolutely with sufficiently high precision nor could it be clarified yet whether the observed mass changes are primarily due to a drift of the NPKs, or of the IPK, or of both.

Unknown changes in the mass unit also influence the electrical units, because the definition of the ampere is related to the kilogram [1]. Similarly, the definitions of the mole and candela also depend on the kilogram [1]. In 1999 the CGPM therefore recommended that efforts be continued to refine experiments linking the unit of mass to fundamental constants with sufficiently high precision (some parts in 10^8) so that the continuity of mass values be ensured after a redefinition of the kilogram.

2. PROPOSED CHANGES TO THE SI

Resolution 1 adopted by the CGPM in 2011 supports the intention to revise the SI with a view that it continues to meet the needs of science, technology, and commerce in the 21st century. The proposed changes to the SI can be summarized as follows [1].

1. Keep the existing seven SI base units, but define them all in terms of seven well-recognized fundamental or atomic constants, such as Planck's constant h.

2. Fix the values of all these constants to an exact number (with zero uncertainty), as is already the case for the speed of light in vacuum, c = 299 792 458 metre per second.

3. Use "explicit-constant" formulations to express the definitions of all seven SI base units in a uniform (but indirect) manner.

4. Draw up specific "*mise en pratique*" (i.e. sets of instructions) for each base unit to explain how the units can be practically realized based on recommended top-level methods.

The kilogram would be defined in terms of Planck's constant h, the ampere in terms of the elementary charge e, the kelvin in terms of Boltzmann's constant k, and the mole in terms of the Avogadro constant N_A.

The second would still be defined in terms of the hyperfine splitting frequency of the ground state of the caesium 133 atom $\Delta\nu(^{133}Cs)_{hfs}$, but the formulation would be changed into an "explicit-constant" one, where the unit (here the second) would be defined indirectly by specifying explicitly an exact value for $\Delta\nu(^{133}Cs)_{hfs}$ (9 192 631 770 hertz). The same would hold for the metre (defined in terms of the speed of light in vacuum c), and the candela (defined in terms of the luminous efficacy K_{cd} of monochromatic radiation of frequency 540 THz).

Resolution 1 (2011) highlights the following advantages of such a "new SI" [1]:

1. The uncertainties of all SI electrical units together with the SI values of the Josephson and von Klitzing constants K_J and R_K would be significantly reduced.

2. The kelvin would no longer be defined in terms of an intrinsic property of water that, while being an invariant of nature, in practice depends on the purity and isotopic composition of the water used.

3. The mole would no longer depend on the definition of the kilogram; this would emphasize the distinction between the quantities "amount of substance" and "mass".

4. The uncertainties of the values of many other important fundamental constants and energy conversion factors would be eliminated or greatly reduced.

3. REDEFINITION OF THE KILOGRAM

In the present SI, one kilogram is defined as exactly the mass of the IPK. According to draft chapter 2 of the 9th SI brochure [2], the new explicit-constant definition of the kilogram would read:

"*The kilogram, kg, is the unit of mass; its magnitude is set by fixing the numerical value of Planck's constant (h) to be equal to exactly 6.626 06X · 10^{-34} when it is expressed in the unit s^{-1} m^2 kg, which is equal to J s.* "

The exact value for X, which will be fixed by the latest CODATA adjustment at the time of the redefinition [3], requires further experimental effort to reach a sufficiently small relative measurement uncertainty in the order of 10^{-8}.

Compared with the redefinition of other base units the redefinition of the kilogram is the most critical one, for several reasons:

- Accurate weighings and mass determinations are of extraordinary importance in science, trade and industry,

- There are partly very high demands on the accuracy of mass determinations. E1 accredited mass laboratories, for instance, keep reference standards with relative uncertainties between $2.5 \cdot 10^{-8}$ and $5 \cdot 10^{-8}$,

- If the value for Planck's constant *h* were fixed too early, there would be a risk of jumps in the order of 10^{-7} in mass values of precision mass standards, with consequences for the adjustment and verification of both class E1 and E2 weights according to OIML R 111 [4].

The Consultative Committee for Mass and Related Quantities (CCM) therefore, at its meeting in 2010, recommended the following conditions to be met before the kilogram is redefined [5]:

1. There shall be at least three independent experiments (Avogadro, watt balances) that yield values for *h* or N_A with relative standard uncertainties not larger than $5 \cdot 10^{-8}$,

2. At least one of the above experiments shall have reached a value for *h* or N_A with a relative standard uncertainty not larger than $2 \cdot 10^{-8}$,

3. The values provided by the different experiments for *h* or N_A shall be consistent at the 95 % level of confidence,

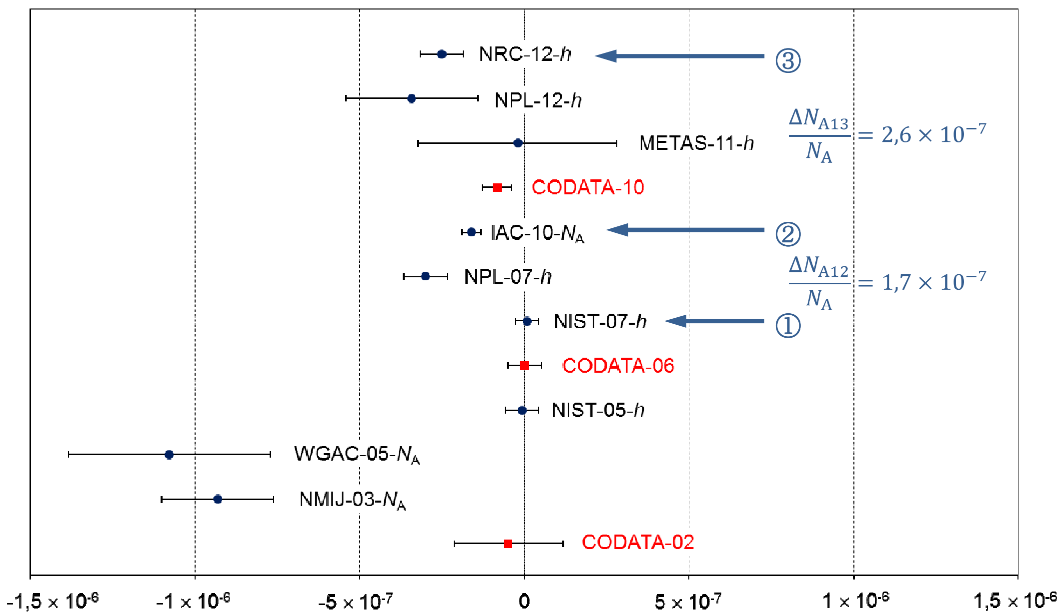

Figure 1: Measurement results for the Avogadro constant N_A with standard uncertainties ($k = 1$), represented as relative deviations from the CODATA 2006 value ($N_A = 6.02214179(30) \times 10^{23}$ mol^{-1}). The results for Planck's constant, *h*, (watt balance) and for K_J (voltage balance) have been converted by means of the CODATA 2006 constants.

Explanations: "NPL-07-*h*", for example, means: NPL's result in 2007 for a measurement of *h*. WGAC: Working Group Avogadro Constant, IAC: International Avogadro Coordination. Currently, the three results with the smallest uncertainties are: (1) NIST-07-*h* ($u_r = 3.6 \times 10^{-8}$), (2) IAC-10-N_A ($u_r = 3.0 \times 10^{-8}$) and (3) NRC-12-*h* ($u_r = 6.5 \times 10^{-8}$).

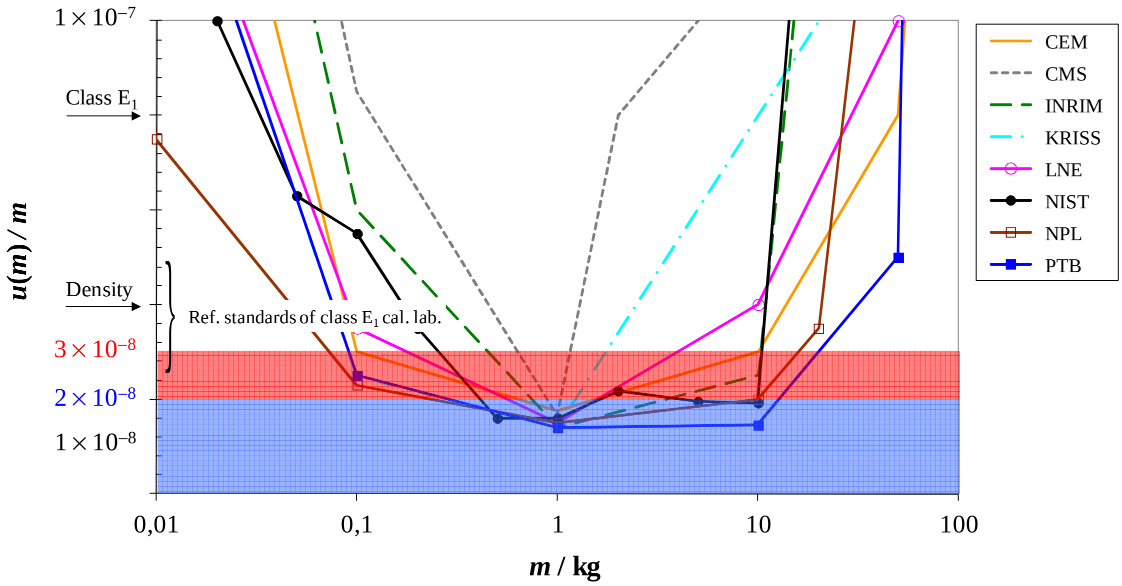

Figure 2: Calibration and Measurement Capabilities (CMCs) for mass standards in the range from 10 g to 100 kg of eight selected NMIs [12] compared with different uncertainty limits for the realization of a redefined kilogram and relative standard uncertainties of the best primary density standards (see pointer "Density"), for reference standards of class E_1 calibration laboratories (see range indicated), and for class E_1 weights (see pointer "Class E_1").

4. Traceability of the BIPM prototypes (and all other mass standards involved in the above experiments) to the IPK shall be confirmed.

The CCM further recommends that a "pool of reference standards" (or “ensemble of reference mass standards”) shall be established at the BIPM to facilitate the dissemination of the redefined kilogram. It further recommends that the BIPM and a sufficient number of National Metrology Institutes (NMIs) continue to develop, operate or improve facilities and experiments that allow the realization of the redefined kilogram with a relative standard uncertainty not larger than $2 \cdot 10^{-8}$.

Most of the CCM conditions and recommendations have not yet been met. The most critical fact is that there are only two experiments up to now that have reached relative uncertainties smaller than $5 \cdot 10^{-8}$ ($3.6 \cdot 10^{-8}$ for the NIST watt balance [6] and $3 \cdot 10^{-8}$ for the Avogadro experiment [7]), where the results are not consistent (figure 1). The discrepancy is considerable and amounts to about $1.7 \cdot 10^{-7}$. The discrepancy between the recently published result of the NRC watt balance [8] and that of the NIST watt balance [6] is even larger and amounts to about $2.6 \cdot 10^{-7}$ (figure 1).

4. CONSEQUENCES FOR MASS METROLOGY

While there is no doubt that a redefinition of the kilogram is desirable from the point of view of fundamental physics, the practical implications of a redefinition must be carefully considered beforehand in order to avoid negative consequences, not only for high-precision mass measurements, but also for the SI in general. Considering the very large importance of weighing instruments, mass comparators and mass standards used in trade, industry and science, and also in daily life, the possible practical consequences and negative implications of a premature or even wrong decision could be tremendous. Despite its limitations, the current definition of the kilogram has quite successfully guaranteed up to now, that - all over the world - high-precision mass standards and weights of accuracy classes E_2, E_1 and even better are calibrated and used in the global market without any problems. Based on the CIPM Mutual Recognition Agreements (MRA) [9] calibration certificates have meanwhile achieved a high degree of worldwide acceptance.

Interestingly, there are only a few publications available about the possible practical consequences of the redefinition of the kilogram [10, 11]. A thorough examination of the realization, dissemination chain and uncertainty propagation for the redefined kilogram shows that:

- If all the above CCM recommendations are closely observed and met, no serious changes in the calibration chain of mass standards will occur, including high-precision mass standards and weights of class E_1,

- However, even if the CCM recommendations are met, the uncertainty values in the "calibration and measurement capabilities" (CMCs) [12] of NMIs will increase by up to a factor of 2, at least in the range from 100 g to 10 kg (figure 2),

- If the CCM recommendations were <u>not</u> met, mass standards of high accuracy with a relative uncertainty smaller than or equal to $4 \cdot 10^{-8}$, as presently offered by NMIs, would no longer be available, and

- There would be the risk that accredited calibration laboratories would no longer be able to calibrate class E_1 weights according to OIML R 111; this would rather be the exclusive task of certain NMIs which have sufficiently accurate mass standards available.

There is another risk of a premature redefinition if one or more of the above CCM conditions are not closely observed or are ignored. Most likely the CODATA recommended values will be the basis for fixing the relevant fundamental constants, which is Planck's constant *h* in case of the kilogram. If one compares the long-term mass changes of platinum-iridium kilogram prototypes with the values of *h* (or N_A) resulting from CODATA adjustments over the past twelve years, within only *four* years these CODATA values "jump" by about $1 \cdot 10^{-7}$, which is a factor of two worse than the assumed instability of the IPK during the past *hundred* years (figure 3). It is obvious that jumps in such orders must at all costs be avoided for mass calibrations, because the consequence for high-precision mass standards would be that after each jump the respective calibration certificates would be invalid and, perhaps, would have to be re-issued by the mass calibration laboratories responsible.

In response to Resolution 1 of the CGPM, the International Organization for Legal Metrology (OIML) has recently carried out an inquiry amongst its member states and some Technical Committees, in order to explore in more detail the possible practical consequences of a revised SI in general, and a redefined kilogram in particular, with the aim to provide an official statement on the proposed revision of the SI. It is expected that the results and the statement will be published soon [14].

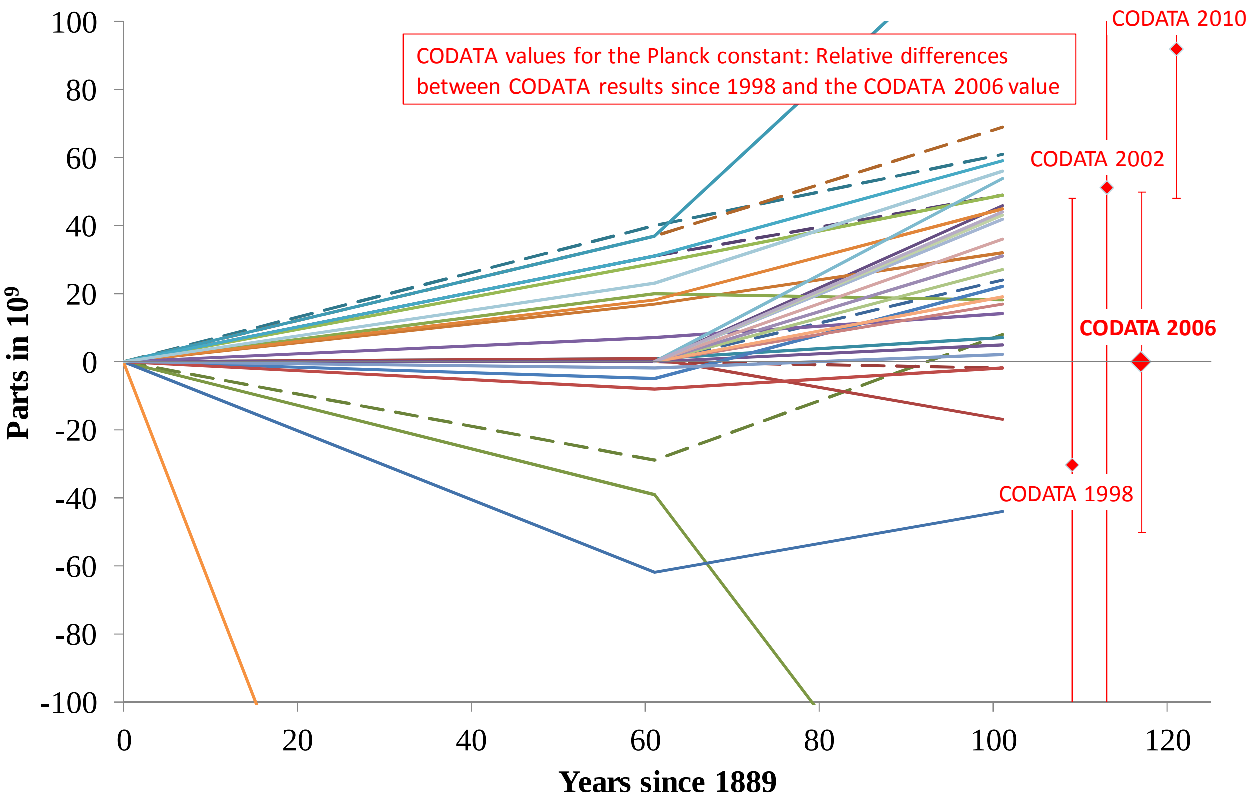

Figure 3: Mass changes of the six official copies (dashed lines) and national prototypes nos. 2 to 55 against the IPK since 1889 [13], compared with relative changes of CODATA values for Planck's constant, *h*, since 1998, where the CODATA 2006 value was (arbitrarily) chosen as a reference value.

5. SUMMARY AND CONCLUSION

This paper outlines the background and most important changes that are proposed to revise the present SI.

It also describes the current status of the redefinition of the kilogram, the relevant experiments, and the respective recommendations of the CCM that are intended to ensure the continuity of mass values before and after the redefinition of the kilogram at a level of about $2 \cdot 10^{-8}$.

It can be shown that if all CCM conditions and recommendations are closely observed and met, no serious changes in the calibration chain of mass standards would occur, although an increase of the best uncertainties of the CMC entries by up to a factor of two must be accepted.

If the conditions of the CCM are not met, however, especially if the experimental results for h and N_A, as presently published, cannot be further improved as regards precision, uncertainty and consistency, a premature redefinition of the kilogram would pose the risk of jumps in future mass values of mass standards in the order of 10^{-7}. In addition, accredited industrial calibration laboratories would probably no longer be able to calibrate class E1 weights according to OIML R 111.

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