On a natural definition of the kilogram and
the ampere

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Abstract

We consider a recent proposal [1] to redefine the kilogram in terms of natural constants. In our opinion, the main objective of the redefinition should be to build such a version of the SI system in which the electric measurements are possible with the highest accuracy in SI units, and not in practical units as now. We emphasize that this objective can be achieved only with a simultaneous redefinition of the kilogram and ampere. This redefinition must be in terms of fixed values of the Planck constant $h$ and the elementary charge $e$. Certain details of the possible redefinition are considered.

This paper considers the recent proposal [1] to redefine the SI kilogram and possibly the ampere in terms of fixed values of fundamental physical constants. This would change the International System of units (the SI) [2], which is a commonly accepted coherent system for all branches of macroscopic measurements in education, sciences and technology. The redefinition [1], which has been suggested in terms of fundamental constants, also indirectly involves certain natural quantum phenomena, which should appear due to realizations of the redefinition.

Some time ago the SI was changed in a similar matter by fixing a value of the speed of light $c$ [3]. However, the present situation is very different. To our opinion the major problem now is that the present high-accuracy
measurements in mechanics and electricity are performed in two different versions of the SI. While macroscopic mass measurements are performed in terms of the SI kilogram, the most accurate electric measurements are performed in terms of the practical units ohm-90 and volt-90. These latter are apparently not consistent with the SI.

Microscopic mass measurements, however, are related to mass determined in unified atomic mass units and in frequency units, i.e., dealing with a value of $mc^2/h$ instead of the mass $m$. Thus, they are measured in units closely related to the ohm-90 and volt-90. For instance, the SI value of $h$ has a larger uncertainty than microscopic mass comparisons, while in the practical units-90 the numerical value of $h$ is known exactly.

The proposal \cite{1} and its numerous considerations in various international commissions have been focussed on the desirability of replacing the definition of the unit for mass measurements, now based on the last artefact of the SI, the kilogram prototype kept at the BIPM in Sèvres, by a definition which is stable and independently reproducible. That mainly focus attention on the kilogram alone, while a redefinition of the ampere is considered as one of a number of unnecessary collateral options.

On contrary, we believe that the gap between the present version of the SI and the system based on the ohm-90 and the volt-90 is a crucial reason to consider such a redefinition. The modern version of the SI \cite{2} was introduced in 1983 by fixing the value of the speed of light $c$ by CIPM \cite{3}, while in 1988 CIPM recommended a departure from the SI by introducing the practical electric units \cite{4} which have been in effect since 1990.

The desirability of resolving the inconsistency between units used in precision electric and macroscopic mass measurements and restoring the SI system as the only system of units for precision macroscopic measurements drives us to a possible redefinition of the kilogram and the ampere at the same time. We note that the gap appeared because the requirement for performing the most precise electric and mass measurements in the SI units was partly inconsistent. It still is and may remain for an uncertain period of time.

The present version of the SI is based on the kilogram prototype and a fixed value of the magnetic constant $\mu_0$, while the practical units are based on fixed values of the von Klitzing constant $R_K$ and the Josephson constant $K_J$ (see Table 1 for the values). If we intend to define a version which allows the derivation of fixed values of $R_K = h/e^2$ and $K_J = 2e/h$, we have to fix values of two fundamental constants, e.g., the Planck constant $h$ and the elementary charge $e$. To fix two values, we must redefine two units at the
same time.

Thus, the necessary requirement for the redefinition to resolve the inconsistency is to redefine two units by fixing values of two fundamental constants at the same time. The redefinition of the kilogram alone would be of a reduced importance.

Most of the fundamental constants are related to microscopic physics (atomic, nuclear or particle physics) and their numerical values are of two kinds being a result of

- a pure microscopic comparison (e.g., a value of $m_e/m_p$);
- a comparison between microscopic and macroscopic values (e.g., a value of the electron mass in kilograms or eV/$c^2$)

The pure microscopic data are more accurate than the data which involve also macroscopic physics and that is mainly a consequence of the limited accuracy of measurements linking macroscopic and atomic physics. Very few numerical values, such as for the gravitation constant $G$, comes from pure macroscopic experiments, and these play only a marginal role in precision measurements.

Apparently, without any new experiments we cannot improve the links between the microscopic and macroscopic physics. However, the numerical values of the fundamental constants play an important role as anchor reference data. For instance, it is customary to express results for X-ray transitions rather in units of energy (eV) than in terms of the frequency or wave length. To interpret the frequency as an energy (in eV), one has to apply a value of $h/e$. We note that the accuracy of comparisons of two transitions is higher than that of the available numerical value of $h/e$ in the SI units [5]. By changing the basis of the definition of the SI units of mass and charge we can improve quality of the reference data, and the characterization of the X-ray transition in terms of electron-volts would be adequate. This could be achieved by defining the units of mass and charge, which are now macroscopic, in microscopic terms, i.e., in terms of $h$ and $e$.

For the SI, the most questionable link between macroscopic and microscopic physics is related to experiments on determination of the Planck constant $h$. There is currently an unresolved discrepancy of 1 ppm between values of the Planck constant derived from the watt-balance experiments and from the X-ray crystal density (XRCD) determination (see, e.g., [5]). The results of all other measurements together produce a third value that is
Table 1: Numerical values of the involved fundamental constants. Here, $u_r$ is a relative standard uncertainty. We used units derived from $\Omega_{90}$ and $V_{90}$, such as $J_{90} = V_{90}^2 s/\Omega_{90}$, $kg_{90} = J_{90} s^2/m^2$ etc. The references are [5] for CODATA and [4] for CIPM. The exact SI values are from [2]. The values marked with the asterisk (*) are derived from related references.

| Constant | Value | Unit | $u_r$ | Comment |
|----------|-------|------|-------|---------|
| $m(\bar{K})$ | 1 | kg | exactly | SI |
| | $1 - 1.0(17) \cdot 10^{-7}$ | kg$_{90}$ | [1.7 $\cdot 10^{-7}$] | CODATA* |
| $c$ | 299 792 458 | m/s | exactly | SI |
| $\mu_0$ | $4\pi \cdot 10^{-7}$ | N/A$^2$ | exactly | SI |
| | $4\pi \cdot 10^{-7} \times (1 - 17.4(3.3) \cdot 10^{-9})$ | N$_{90}$/A$_{90}^2$ | [3.3 $\cdot 10^{-9}$] | CODATA* |
| $e$ | 1.602 176 53(14) $\cdot 10^{-19}$ | C | [1.7 $\cdot 10^{-7}$] | CODATA |
| | 1.602 176 49(66) $\cdot 10^{-19}$ | C | [4.1 $\cdot 10^{-7}$] | CIPM* |
| | 1.602 176 492 $\ldots$ $\cdot 10^{-19}$ | C$_{90}$ | | exactly | CIPM |
| $h$ | 6.626 069 3(11) $\cdot 10^{-34}$ | Js | [1.7 $\cdot 10^{-7}$] | CODATA |
| | 6.626 068 9(38) $\cdot 10^{-34}$ | Js | [5.7 $\cdot 10^{-7}$] | CIPM* |
| | 6.626 068 854 $\ldots$ $\cdot 10^{-34}$ | J$_{90}$ s | | exactly | CIPM |
| $R_K$ | 25 812.807 449(86) | $\Omega$ | [3.3 $\cdot 10^{-9}$] | CODATA |
| | 25 812.807 0(25) | $\Omega$ | [1 $\cdot 10^{-7}$] | CIPM |
| | 25 812.807 | $\Omega_{90}$ | | exactly | CIPM |
| $K_J$ | 483 597.879(41) $\cdot 10^9$ | Hz/V | [8.5 $\cdot 10^{-8}$] | CODATA |
| | 483 597.9(2) $\cdot 10^9$ | Hz/V | [4 $\cdot 10^{-7}$] | CIPM |
| | 483 597.9 $\cdot 10^9$ | Hz/V$_{90}$ | | exactly | CIPM |
| $N_A$ | 6.022 141 5(10) $\cdot 10^{23}$ | 1/mol | [1.7 $\cdot 10^{-7}$] | CODATA |
| $h N_A$ | 3.990 312 716(27) $\times 10^{-10}$ | J s/mol | [6.7 $\cdot 10^{-9}$] | CODATA |
competitive in accuracy with the XRCD result and is in a perfect agreement with the watt-balance values (see Fig. 1). The importance of this third result is often underplayed.

![Diagram of Planck constant determinations](image)

Figure 1: Present determinations of the Planck constant $h$. The watt-balance values (NIST-98 and NPL-90) and XRCD result ($V_m(Si)$) are taken directly from [5] and labelled in the same way as there. *Others* stands for the average values of the rest of the data and was communicated to me by Peter Mohr on base of [5]. The vertical line indicates a numerical value of $h$ in practical units [4].

These experiments determine a link between the macroscopic mass unit, the kilogram, and the electric power unit expressed in terms of volt-90 and ohm-90. This is the crucial link for the realization of the SI ampere in the present version of the SI. In the proposed version of the SI [1], based on the kilogram unit defined by a fixed value of the Planck constant $h$ or the Avogadro constant $N_A$, these experiments determine the mass of the kilogram prototype.

Recently a number of international commissions and committees considered this issue. They emphasized the importance of the problem related to this link and its undesirable effect on accuracy in mass measurements in the case of the redefinition. Their concerns are based on an assumption that it is up to those who decide on the redefinition to involve this link into the SI or not. We agree that this link is a great problem. But we unfortunately
disagree that this link can be avoided by, e.g., postponing the redefinition of the kilogram. This link, as we mention above, is crucial in present-day realizations of the ampere (and the volt) of the SI. In other words, it has been used at least from 1990 for the realization of the SI ampere and there is no way to avoid this troubled link.

We also raise a question about the conceptual difference between a constant-based unit and an artefact-based unit. In the latter case, the definition can have fundamental problems, but it is very instructive. It is clear in a practical sense what the unit is and, in the most of comparisons, the method of the comparison is also obviously fixed. There is not much room for any variety in realizing the standards. In the former case, when a unit is based on a constant and certain relations to other quantities (i.e. certain physical laws), there are a number of ways to realize the definition and, as in the case of any scientific experiment, the results may disagree. A substantial difference for a constant-based unit and an artefact-base unit is due to possible systematic effects. For the artefact, the systematic effects may take place, but be reproducible. That is an advantage of the artefact from a practical point of view. However, such a systematic effect, being invisible, can produce a drift of the unit or a reproducible systematic shift (if a way of comparison is compromised). Various differences in possible realizations of the constant-based units may produce a discrepancy but that would allow detection of a possible problem. The very opportunity to discover the problem, even accompanied by possible discrepancies, is an advantage.

In the case of a constant-based unit, the systematic effects may be different. For instance, for determination of the Planck constant, which is the realization of the SI ampere (presently) and of the SI kilogram (in the case of the redefinition), these effects are different and particular results disagree with each other. Relative mass measurements and relative electric measurements are more accurate than the link. For the electric units, CIPM has chosen a clear strategy. A conservative result for the Planck constant (and, consequently, for the realization of the SI volt and ampere) has been accepted \[1\], while the most accurate measurements are to be performed in practical

\[1\] We have to note that any legal adoption of any scientific result (as, e.g., various *mise en pratique*) is an introduction of a non-SI unit. The SI is a closed system of definitions. Adoption of anything else as a part of the SI changes the system, while adoption of anything beyond the SI leads to practical units. In particular, once the accuracy for the SI values of \(K_J\) and \(R_K\) is adopted, we arrive at a contradiction between the CIPM recommendation \[4\] and the accuracy determined by scientific means \[5\], which is a result
units. The same approach should be used for the kilogram in the case of the redefinition.

In principle, after the redefinition of the kilogram and progress in its realization, another situation could take place. It may happen that uncertainty of best realizations and even their discrepancy (if any) could be smaller than uncertainty related to the prototype. What strategy should be used to deal with a possible discrepancy (which in principle could appear from time to time for any constant-based units)? As long as one particular method could provide us with reproducible results we should accept it to define a practical unit, while the related SI unit would be still defined in a conservative way.

Let us to look now into possible consequences of the redefinition. First, we need to stress that the only reasonable version of such a redefinition is to fix $h$ and $e$. We can present certain advantages in fixing $h$ instead of $N_A$ for the redefinition of the kilogram only. In particular, the variety, a relatively low degree of interdependence, and the level of accuracy that has been achieved makes watt-balance experiment more desirable than the XRCD measurement. The watt-balance experiment would be a preferred realization of the kilogram if the Planck constant $h$ is fixed. On the other hand, the XRCD technique is the most natural choice for the kilogram based on a fixed value of $N_A$.

One should not overestimate importance of these straightforward preferences, which are rather educational and practical. However, they may become of practical importance if the accuracy of mass measurements increases. As shown in Table 1, the uncertainty of the molar Planck constant $h N_A$ is below 10 ppb. If we fix one of these two constants, this value would be the uncertainty of the other. At the present level of accuracy in maintaining the kilogram, in mass measurements and in the link between the kilogram and the electric units, this uncertainty is as good as zero. The accuracy of the link (i.e. of the present-day determinations of $h$ and $N_A$ separately) for a number of experimental reasons should be substantially lower than that of the $h N_A$ for a long but uncertain period of time. For a redefinition of the kilogram alone, it does not much matter which of these two constants to fix.

However, we have to redefine the kilogram and the ampere at the same time. We should clearly choose a redefinition that will produce fixed values of $R_K$ and $K_I$ to preserve the advantages of using the present-day practical units. There is no way to do that unless we fix $h$ and $e$, and we consider...
this scenario below. In contrast, if the values of $N_A$ and $e$ are fixed instead, the electrical community would still need practical units of resistance and potential. The accuracy of the SI measurements of those quantities would increase in comparison with the present situation, but still would be below the one accessible in terms of the practical units.

If the value of $h$ and $e$ were fixed, then the uncertainties of the Avogadro constant, the mass of the electron, proton, and various atoms and nuclei would be substantially smaller. The uncertainties of the Rydberg constant and various other frequencies expressed in eV would be greatly improved as well. The uncertainties of the many electrical measurements in SI units would be obviously substantially smaller.

Unfortunately, the proposal would have an undesirable effect on the macroscopic mass measurements in SI units. The consequences of such effects should be prevented by using the existing prototype of the kilogram in a way similar to the way the quantum Hall and Josephson standards are used now. Measurements in terms of the unit determined by the existing prototype would be considered measurements in conventional units recommended by CIPM for a transition period. Macroscopic mass measurements in SI units could be performed by comparison to the existing prototype together with its calibration by the measurements which now serve as determinations of the Planck constant.

How large could the undesirable effects be? At one time it was assumed that a 10-ppb uncertainty in experiments relating macroscopic and microscopic masses would be desirable in order to implement a redefinition of the kilogram. However, it is now felt that this is not realistic or necessary, particularly in view of the instability of the mass of the kilogram. In fact, its mass changed by more than 60 ppb when it was last washed in the verification in 1988–1992 (see, e.g., [1]). However, this level of accuracy is needed only for experiments like determination of $h$ and $N_A$. Accuracy, needed for practical applications is at the level of few parts in $10^7$. Indeed, we should like to have more accurate standards to perform various tests, but such tests on, e.g., consistency of various national standards, may be performed in practical units.

Since the current definition of the SI ampere was essentially abandoned by the electrical community when conventional values of the von Klitzing and Josephson constants were introduced in 1988, there would be no discontinuity in the electrical units if the ampere were redefined to make the elementary charge $e$ exact and the kilogram were defined via a fixed value of $h$. In fact,
there would be a significant gain in precision of SI electrical units, because
the SI ohm and volt would be exactly defined in terms of the quantum Hall
and Josephson effects. The present CIPM recommendations [4] on the ohm-
90 and volt-90 set the uncertainty at the level of one and four parts in 10^7,
respectively, while the most accurate measurements in practical units are
done at the level of few parts in 10^9 and such measurements are of practical
interest.

The accuracy, continuity, and stability of the units and of the fundamental
constants is critical to the scientific community. In principle the requirement
for the continuity of various units and constants may be controversial. In
particular, the suggested units, obtained by fixing \( h \) and \( e \), will not neces-
sarily be the same as conventional units, since corrections to the standard
expressions for \( R_K \) and \( K_J \) in terms \( h \) and \( e \) of are possible.

There are basically two options.

- We can set new ohm and new volt to be the same as volt-90 and ohm-90
  (except for the necessity of rounding the values in the definitions). In
  this case all results in practical units will be accepted as the SI results,
  while value of the kilogram and certain fundamental constants will
  jump (numerical values of some constants in the SI units and units-90
  are presented in Table 1).

- We can choose an option to adopt values of \( h \) and \( e \) as they are in
  the CODATA paper [5] (or the newest available CODATA results at
  the time of the redefinition). That will reduce a possible jump^2 in the
  kilogram of SI and values of the fundamental constants.

Technically we can fix first \( R_K \) and \( K_J \), calculate \( h \) and \( e \), and round

\[^2\text{The very existence of the jump becomes questionable and some believe that there}
\text{would be no jump at all. We choose here to use a common word ‘jump’ instead of ‘discon-
\text{tinuity’ because in a sense there would be no discontinuity, but there should be a certain}
\text{jump. The jump would be a result of a two-step action. For instance, we use an exact
\text{value of \( \mu_0 \) [2]. With the redefinition, we make it measurable. Once we use the CODATA}
\text{data (see Table 1), the new result for \( \mu_0 = 2 \alpha R_K / c \) should have an uncertainty. The new}
\text{result may be consistent with the presently fixed value of \( \mu_0 \) [2]. Nevertheless, sooner or}
\text{later with improvement of accuracy, a value of \( \mu_0 \) would depart from the previously fixed}
\text{numerical value. There is no chance that we can guess the values for \( e \) and \( h \) in such a}
\text{way that the measurable \( \mu_0 \) would be exactly the same as before. That is the same as}
\text{trying to guess an exact value of the fine structure constant \( \alpha \). So, eventually a certain}
\text{jump would take place, but in each step we should have no discontinuity.}
\]
them properly at the end. It is more transparent to discuss consequences of fixing different values of \( R_K \) and \( K_J \) than of \( h \) and \( e \).

At present, CODATA’s \( \{ R_K \}_{\text{SI}} \) differs from CIPM’s \( \{ R_K \}_{90} \) by approximately five standard deviations (see Table I) and we have to choose between them. On the other hand, CODATA’s \( \{ K_J \}_{\text{SI}} \) differs from CIPM’s \( \{ K_J \}_{90} \) by less than one standard deviations (see Fig. I) and we can choose either of them without any serious consequences.

A choice between different values of \( R_K \) would affect a value of \( \mu_0 \) and a possible departure of the new SI ohm from the present SI ohm. If we choose the CIPM’s value, the new ohm SI would be related to ohm-90 and to the present CIPM central value of the SI ohm (we cannot discuss here the SI ampere because its definition involve \( \mu_0 \) and the kilogram, which is also a subject of changes). A value of \( \mu_0 \) would depart from its present value, but it is not particularly important for precision measurements. The only experiments are with calculable capacitors, but there are very few of them around the world and a shift at the level below 20 ppb is not important at their present level of realization.

In principle, impact of choice between different values of \( K_J \) could be more important. Different \( K_J \) would lead to different values of the kilogram, the volt and the ampere and different numerical values of various important fundamental constants such as \( h, e, \) particle masses in kilograms and eV/c\(^2\), and energy of various atomic and nuclear transitions in electron volts. Fortunately, as we mention above, CODATA’s \( \{ K_J \}_{\text{SI}} \) and CIPM’s \( \{ K_J \}_{90} \) agree to each other within a standard deviation (the difference is approximately half a deviation) and perhaps, because of this agreement, we should choose the CIPM’s value. A change in a value of the fundamental constants within one sigma is not a discontinuity, and we would prefer to set the redefined SI units to be equal to the practical units.

That does not downplay the importance of the CODATA values. The CODATA evaluation will determine a recommended value of the magnetic constant \( \mu_0 \) and a value of the mass of the prototype \( m(K) \). The situation with \( K_J \) may change by 2007 and with new watt-balance and XRCD results the CODATA’s \( \{ K_J \}_{\text{SI}} \) could depart from \( \{ K_J \}_{90} \). If the difference would be above one standard deviation we will need to make a real choice between CODATA’s and CIPM’s values.

We believe that the kilogram and the ampere should be redefined and that they should be redefined at the same time by fixing values of the fundamental constants \( h \) and \( e \). Two open practical questions are related to choice for the
fixed values (discussed above) and to a proper time for the redefinition. A choice for the timing should consider the following.

- Any decision (positive or negative) on the redefinition will have benefits and expenses. These have to be examined carefully.

- Some disadvantages (discontinuity in values of units and numerical values of the constants, worsening of accuracy of measurements in SI units, etc.) may be unavoidable. It is necessary to take into account that postponing a necessary decision could increase expenses.

Considering the advantages and disadvantages we point that

- from the point of view of mass metrology, the redefinition of the kilogram will be successful once the Planck constant is reliably determined with a standard uncertainty less than about 50 ppb;

- from the point of view of electric measurements, the redefinition will be successful even now because of the immediate improvement in accuracy of precision electric measurements in SI units;

- the final decision on the proper time for the redefinition of the kilogram and the ampere can be made when there is a net gain based on a careful comparison of the advantages and disadvantages. Careful examination should be given to the relative importance to the fields of electric and mass measurements (accuracy, volume of measurements, area of applications etc.) where the changes would take place.

The standards themselves have no value if they are not needed for actual or future applications. For this it is most important for us is to consider the consequences outside of the standards community. Metrologists are trained to deal with different units (the SI units and various practical units), while outside people are not. There is a limited number of scientific experiments were such a level of accuracy is important. Improvement of the reference data is clearly an advantage for outsiders.

We hope that a real study on the practical importance of precision mass and electric measurements with uncertainty below a 100 ppb will be done. Up to now, despite numerous considerations of the redefinition, this question has not been discussed at all, or at least the results of such a discussion have not been made available.
This paper is an extended version of document CCU/05-27, a working document of the 17th meeting of of Consultative Commitee for Units. During discussions there and at the preceding meeting of the CODATA task group on fundamental constants, it became clear for me that the accuracy actually demanded in precision electric measurements are about two orders of magnitude higher than in mass measurements. Still, examination of the problem is necessary, because a question is not only accuracy, but also number of the measurements.

To conclude this paper let us suggest wording for the redefinition of the kilogram: “The kilogram is the mass of a body whose rest energy is equal to the energy of $299.792.458 \cdot 10^{27}$ optical photons in vacuum of wavelength of $66.606.9311$ nanometres.” The explicit indication of the number of the photons is necessary. The kilogram is a macroscopic quantity, while we try to link it to a microscopic object. With a single microscopic object we arrive at the situation when the energy is bigger than the Planck energy or the wave length is shorter than the Planck length.

Concerning the ampere, a redefinition in terms of the elementary charge is rather trivial. Still, it should be mentioned, that, when the definition of the ampere was adopted, its direct realization was possible. Now, we see that there are two units (the ohm and the volt), which we can realize directly and two units (the ampere and the coulomb) which are related to more fundamental quantities but cannot be realized directly. In former time, the ampere was a good choice. Now, if we like to make a practical choice it should favors the volt (potential is more fundamental than resistance), and if we like to make a physical choice we should prefer the coulomb (in particular, because of its educational advantages). There are no advantages for the ampere anymore.

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I discussed the issue on the number of the photons with Peter Mohr and it resulted in footnote 2 in [1]. I need to mention that I am impressed by elegancy of the solution there of another problem of the definition, which is avoiding of a multiplication and division of numerical values of constants $c$ and $h$ in such a combination as $\{c\}^2/\{h\}$. The version presented here is somewhat different from that in [1]. From a point of view of relativistic physics it is preferable to speak in terms of the rest energy rather than the rest mass (see, e.g., [3]).
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