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Dissemination of the kilogram via silicon spheres

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Abstract
An alternative method to realize and disseminate the unit of mass, kilogram, as it will be defined in the revised International System of Units (SI) in 2018, is presented. The new approach allows to relate the Planck constant, *h*, to spheres manufactured from natural silicon (Si). Fundamentally, the Physikalisch-Technische Bundesanstalt (PTB) aims for a primary realization of the kilogram by linking the fixed value of *h* to spheres manufactured from monocrystalline silicon crystals, which are highly enriched in the isotope ^{28}Si. However, since the process for obtaining these crystals is sophisticated and, hence, expensive, disseminating the kilogram by means of ^{28}Si spheres is economically hardly feasible.
To address this issue, a "quasi-primary" realization of the kilogram will be established at PTB. The precisely known isotopical composition of a ^{28}Si sphere will be transferred to spheres manufactured from monocrystalline, natural silicon by means of hydrostatic weighing. For the dissemination of the kilogram with these more favourable "quasi-primary" Si spheres, a relative uncertainty of 3×10^{-8} at 1 kg has to be achieved. Accordingly, the accuracy of the hydrostatic weighing has to exceed that of the well-known apparatuses for precision density measurements of solid materials by one order of magnitude. To this end, a new apparatus will be set up at PTB, which combines the Archimedes (buoyancy) principle with a magnetic suspension coupling. This combination *e.g.* allows to improve one of the major uncertainty contributions: the temperature stability in the measuring cell.

Avogadro constant, dissemination, hydrostatic weighing, kilogram, magnetic suspension coupling, Planck constant, silicon spheres

1. Introduction

In 2018 the General Conference on Weights and Measures (CGPM) is expected to revise the International System of Units (SI) fundamentally. In the future, all seven base units will be fixed by a combination of defining constants. This revision will bring significant changes to the unit of mass, the kilogram: currently, the kilogram is defined and realized by an artefact, the International Prototype of the Kilogram (IPK). However, in the future the kilogram will be defined by a fixed value of the Planck constant, *h*. Accordingly, the theoretical definition of the kilogram has to be linked to a macroscopic object by means of an experiment.

Nowadays, there a two independent types of experiments suited for a primary realization of the redefined kilogram with a sufficiently low uncertainty: the watt balance [1] and the x-ray crystal density (XRCD) method [2]. The Physikalisch-Technische Bundesanstalt (PTB) pursues a primary realization of the kilogram utilizing the XRCD method, whereby the fixed value of the Planck constant is linked to monocrystalline silicon (Si) spheres with known lattice parameter, volume, and density. The determination of the density of the silicon by measuring its isotopical composition was thereby a limiting factor [3] to achieve the desired relative uncertainty of 2×10^{-8} at 1 kg. Therefore, the silicon spheres are nowadays manufactured from monocrystalline silicon crystals, which are highly enriched in the isotope ^{28}Si [2]. However, the process for obtaining these crystals is sophisticated and, hence, expensive. Accordingly, disseminating the unit kilogram by means of ^{28}Si spheres seems economically hardly feasible.

Therefore, PTB is currently investigating a novel method to realize the kilogram by means of more favourable spheres, which are manufactured from monocrystalline, natural silicon. For this so-called "quasi-primary" realization, the precisely known isotopical composition of a ^{28}Si sphere will be transferred to Si spheres by means of hydrostatic weighing. To be able to meet the requirements of designated institutes and calibration laboratories for the dissemination of the kilogram by means of natural Si spheres, the uncertainty of the "quasi-primary" realization must be in the order of 3×10^{-8} at 1 kg. To achieve this ambitious objective, the accuracy of the hydrostatic weighing has to exceed that of the well-known apparatuses for precision density measurements [4, 5] of solid materials by one order of magnitude. Therefore, a new apparatus will be set up at PTB, which combines the Archimedes (buoyancy) principle with a magnetic suspension coupling [6].

The principle of the "quasi-primary" realization of the kilogram and the design concept of the hydrostatic comparator is presented in this publication.

2. A novel method for a "quasi-primary" realization of the kilogram

The "quasi-primary" realization of the kilogram by means of Si spheres will provide a robust, more affordable, but slightly less accurate way to realize and disseminate the kilogram. Hence, the "quasi-primary" realization will not affect the efforts of PTB to establish a primary realization of the kilogram by means of ^{28}Si spheres. Precisely, the "quasi-primary" realization largely relies on the findings of the longstanding, extensive research performed on the XRCD method by the International Avogadro Coordination (IAC) and ^{28}Si spheres will be a key component of the principle of the "quasi-primary" realization.

2.1. Principle of the "quasi-primary" realization of the kilogram

The "quasi-primary" realization of the kilogram depends on the accurately known density of a ^{28}Si sphere. Therefore, the molar mass (*i.e.* the isotopical composition) and the lattice parameter of the isotopical enriched silicon must be measured once. By means of hydrostatic weighing in a transfer fluid (*e.g.* water) the densities of the ^{28}Si sphere and the natural Si sphere will be compared directly in such a way that the mass and the volume of the ^{28}Si sphere do not have to be known. Consequently, the ^{28}Si sphere is not acting as a mass standard.

The natural Si spheres will be manufactured alike the ^{28}Si spheres, *e.g.* the roundness and the surface finish have to meet the same high demands as for the primary ^{28}Si spheres. This allows to determine *e.g.* the surface layers and the volume of the "quasi-primary" Si spheres with the same accuracy as it is performed for the primary realization.

2.2. Design concept of the hydrostatic comparator for the density transfer measurements

The main influence on the overall uncertainty of the "quasi-primary" realization will be the uncertainty of the density transfer by means of hydrostatic weighing. Apparatuses which apply the Archimedes (buoyancy) principle for the determination of the density of solids can be found frequently in scientific literature [4, 5] and such a type of instrument is used at PTB for density calibrations for nearly 30 years [4]. However, even the most accurate devices achieve only relative uncertainties around 20×10^{-8}, which is about one order of magnitude too high for the "quasi-primary" realization.

The major uncertainty contribution for these conventional hydrostatic weighing apparatuses arises from the temperature stability of the transfer fluid. Since the solid sample is attached to the analytical balance via a thin wire, the measuring cell must be open at the top. This limits the potential for improving the temperature control of the measuring cell for the conventional apparatuses. Therefore, a new apparatus will be set up at PTB, which will combine the Archimedes (buoyancy) principle with a magnetic suspension coupling—see figure 1 for a schematic of the planned hydrostatic comparator. The magnetic suspension coupling allows to transfer the load of the solid sample contactless to the analytical balance. Thus, no continuous wire will be needed to attach the sample to the balance and, hence, the measuring cell of the new apparatus can be closed nearly completely.

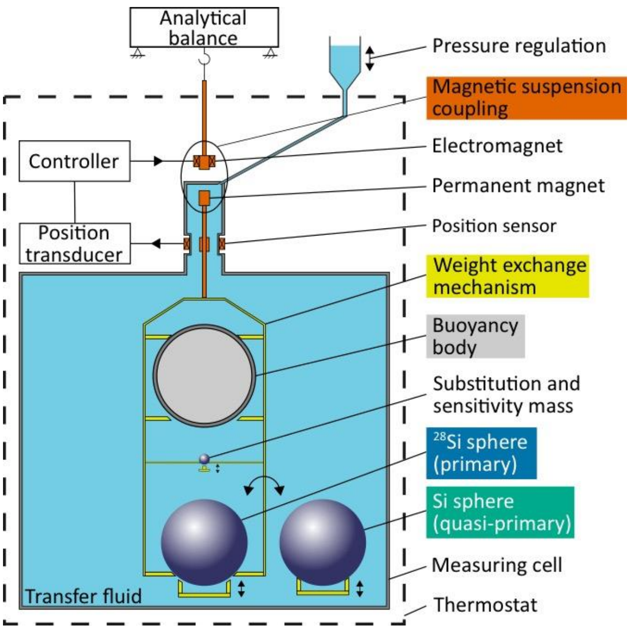

Figure 1. Basic principle of the hydrostatic comparator.

Magnetic suspension couplings are nowadays commercially available by Rubotherm. However, the apparatuses are mainly designed for density measurements in gases over wide pressure and temperature ranges [6]—applications for measurements in liquids or with high loads are not part of the standard product range. Currently, a custom-made magnetic suspension coupling is designed in collaboration with Rubotherm. To achieve the desired relative uncertainty of 3×10^{-8} for the density transfer, a focus during the design process is on the force transmission error [7] of the magnet suspension coupling. For example, a special, differential weighing scheme will be applied and a substitution mass will ensure that the load on the coupling remains constant for all weighings. Furthermore, the density of the transfer liquid has to be known accurately, that is why a measurement of the liquid density has to be integrated in to the set-up as well.

3. Conclusion

A new, alternative way to realize the unit kilogram utilizing spheres manufactured from monocrystalline, natural silicon is presented. The so-called "quasi-primary" realization will allow a robust, more affordable, but slightly less accurate way to realize the unit kilogram than the already known primary realization by means of ^{28}Si spheres. Therefore, it is especially well suited to meet the demands of designated institutes and calibration laboratories for the dissemination of the kilogram after the revision of the SI. The principle of the "quasi-primary" realization requires to set up a new hydrostatic comparator to accurately transfer the well-known density of a ^{28}Si sphere to a natural Si sphere. To achieve a very low measurement uncertainty, this apparatus will combine the Archimedes (buoyancy) principle with a magnetic suspension coupling, which will help to improve the temperature stability of the transfer fluid in the measuring cell.

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