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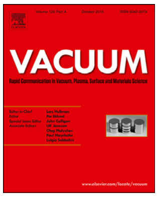

Invited review

Practical requirements for the successful implementation and subsequent dissemination of the redefined kilogram

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ABSTRACT

The kilogram is the last of the seven base units of the SI to be defined in terms of a material artefact rather than by relation to an invariant of nature. Progress is being made towards a redefinition in terms of the Planck constant realised via the watt balance and Avogadro experiments. The accuracy of these experiments is now at the level required by the mass community (2 parts in 10^8) and it is likely that the redefinition will be ratified in late 2018. The change to the definition of the kilogram presents issues which need to be addressed in order to effectively implement the redefinition, to ensure continuity of the mass scale and to efficiently disseminate the new definition to the user community. After redefinition the realisation of the SI unit of mass will be possible via either the Avogadro or watt balance approaches. The two experiments work in a vacuum and so a link between mass standards in air (such as the International Prototype Kilogram used to realise the current mass unit) and standards realised in vacuum will need to be established for initially fixing the Planck constant and subsequently for dissemination of the unit of mass. This paper describes research undertaken to prepare for the redefinition. Next generation mass standards, compatible with use in vacuum, have been developed to improve mass stability while optimising vacuum/air transfer characteristics. Methods for the transfer between and storage in vacuum, inert gas and air have been investigated both gravimetrically and using surface analysis techniques such as X-ray photoelectron spectroscopy (XPS) to characterise surface sorption effects. Additionally new cleaning techniques for primary mass standards using UV activated ozone and low pressure plasma have been developed to replace current manual cleaning methods. The implementation of this research will ensure the maximum benefit is realised from the redefinition of the kilogram in terms of a fundamental constant.

1. Introduction

In the next few years the world's measurement system, the SI, will undergo a major change. Part of this change will be the replacement of the existing definition of the kilogram, which depends on the stability of an artefact made in the 19th century, with a definition based on a constant, the Planck constant h, which lies at the heart of modern quantum physics. This change will strengthen, stabilise, and reunify the SI and, in addition, provide advantages to science and engineering.

The kilogram is the last of the seven base units of the SI to be defined in terms of a material artefact rather than by relation to an invariant of nature. Progress is being made in the development and improvement of methods to realise the kilogram in terms of the Planck constant via the watt balance and X-ray crystal density (XRCD) (or Avogadro) experiments. The accuracy of these experiments are either at or near the requirements of the mass community (2 parts in 10^8) and it is likely that the redefinition will be ratified in late 2018.

While achieving the aim of ensuring the long term stability of the unit of mass, the change to the definition of the kilogram presents issues which need to be addressed in order to effectively implement the redefinition, to ensure continuity of the mass scale and to efficiently disseminate the new definition to the user community. After redefinition the realisation of the SI unit of mass will be possible via either the Avogadro or watt balance approaches. Due to the nature of the two experiments both will realise the kilogram in a vacuum and so a link between mass standards in air

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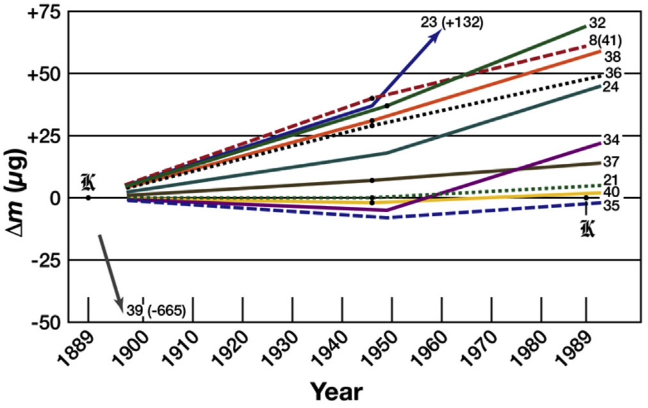

Fig. 1. Mass deviation (Δm) for copies of the international prototype kilogram, identified by number, with respect to the weight itself, measured at the Periodic Verifications.

(such as the International Prototype Kilogram used to realise the current mass unit) and standards realised in vacuum will need to be established, initially in order to fix the Planck constant with reference to the current mass scale and subsequently for dissemination of the unit of mass from the primary realisation experiments.

2. The current definition and its limitations

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram (IPK). The use of an artefact clearly limits the ultimate stability with which the unit can be defined. Fig. 1 illustrates the typical deviation of copies of IPK with relation to the standard itself. Typical deviations of up to 50 µg can be experienced although more recent calibrations at the BIPM have suggested that carefully stored platinum–iridium standards are more stable [1]. Nevertheless, an artefact based standard is susceptible to drift, particularly in the long term.

3. Progress towards the redefinition

The CIPM Consultative Committee for Mass and Related Quantities has made the recommendation that, in order for the redefinition of the kilogram to be ratified, the following conditions are met [2];

- at least three independent experiments, including work from watt balance and XRCD experiments, yield consistent values of the Planck constant with relative standard uncertainties not larger than 5 parts in 10^8,
- at least one of these results should have a relative standard uncertainty not larger than 2 parts in 10^8.

At present at least one watt balance experiment [3,4] and the result from the International Avogadro Coordination (IAC) [5] are at or near the uncertainty of 2 in 10^8, and the results for the value of h are consistent. Further watt balance experiments are at various stages of development and should be able to provide at least a third independent realisation of h by 2017.

4. The primary realisation experiments

4.1. Watt balance

The watt balance [6,7] was conceived by Kibble at the National Physical Laboratory (NPL). The principal of operation is shown diagrammatically in Fig. 2(a) and (b).

The balance measures mass by comparing virtual electrical and mechanical power, $VI = Mgu$. The voltage V and velocity u are measured during one stage of the experiment, Fig. 2(a), and the current I and the weight Mg of the mass M are measured in a separate stage, Fig. 2(b). The two stages are linked using a coil of wire of length l placed perpendicular to the field B of a strong magnet, the two stage process eliminates the need to determine the values of B and l (they just need to be stable between the two phases of the measurement). The electrical quantities, voltage and resistance, can be measured in terms of the Planck constant via quantum mechanical effects: the Josephson effect and the quantum Hall effect (QHE) respectively. The Josephson effect occurs in superconducting systems at low temperatures (usually about 4 K) and can be harnessed to produce a standard voltage. The QHE occurs in particular semiconductor structures at low temperatures and provides a standard resistance. Fig. 3 shows the NPL watt

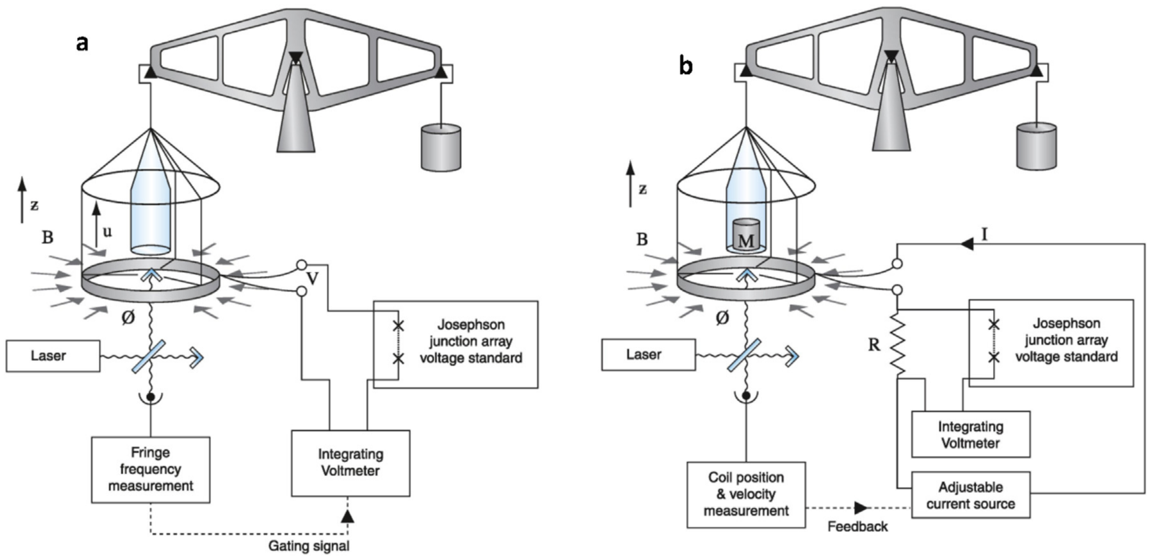

Fig. 2. a: Principle of operation of the watt balance, moving phase. b: Principle of operation of the watt balance, weighing phase.