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Realisation of the awaited definition of the kilogram

Background

In 2011, the 24th General Conference on Weights and Measures recommended that the International System of Units (SI) will be upgraded in terms of fundamental constants. Accordingly, experiments to measure the SI value of the Planck or the Avogadro constants -- hence, necessarily, in terms of the mass of the international prototype -- are necessary to be reversed to give any mass in terms of an internationally agreed numerical value of the Planck constant.

Needs for the project

The figure 1 shows that the mass of the international prototype of the kilogram, which is 1 kg by definition, is drifting with respect to the mass of its official copies. After three verifications, carried out in 1889, 1946, and 1989, a drift of about 50 µg per century has been observed. This drift and the use of quantum effects to realize the volt and ohm are straining the SI. Therefore, the monitoring of the prototype mass-stability, a kilogram redefinition based on the Planck constant, and the link of mass and electrical metrologies are on the top of the metrology agenda. To achieve these objectives, both the watt-balance experiment -- to measure the Planck constant -- and the counting of the atoms in $^{28}$Si spheres -- to measure the Avogadro constant -- are under consideration.

In the watt-balance experiment, the integration of mechanical and electrical measurements allows the $h/m$ ratio, where $m$ is the mass of the international prototype of the kilogram, to be determined. In other experiments, energy or momentum are measured in terms of frequency or wavelength via $E=hf$, where $f$ is the frequency, and $p=h/\lambda$, where $\lambda$ is the wavelength. Since energy and momentum are related to mass by $E=mc^2$ and $p=mv$, where $v$ is the velocity, the quotient $h/m$ is also determined, where $m$ is the mass of an atom or of a particle. Since only the relative atomic masses are well known, these experiments deliver only the value of the $N_A h$ product. In this case, the link to macroscopic masses is made by measuring the Avogadro constant, $N_A$, by silicon spheres of known composition, volume, and lattice parameter.
Fig. 2 – Results of the most accurate determinations of the Planck constant. The reference, $h_0 = 6.62606957 \times 10^{-34}$ Js, is the CODATA 2010 recommended value. The pink band indicates the uncertainty required to ensure continuity to mass metrology.

Scientific and technical objectives

The project brings together experts from institutions across Europe and Japan; the Istituto di Nazionale di Ricerca Metrologica (INRIM – Italy), the Conservatoire National des Arts et Métiers (CNAM – France), the Eidgenoessisches Justiz- und Polizeidepartement (EJPD-METAS – Switzerland), the Observatoire de Paris (OBSPARIS – France), the Laboratoire National de Métrologie et d’Essais (LNE – France), the Physikalisch-Technische Bundesanstalt (PTB – Germany), the National Metrology Institute of Japan (NMIJ – Japan), the Leibniz-Institute of Surface Modification (IOM – Germany), the Bureau International des Poids et Mesures (BIPM), the Laboratoire de Systèmes Robotiques of the Ecole Polytechnique Fédérale de Lausanne (EPFL-LSRO, Switzerland), the European Organization for Nuclear Research (CERN), and the Mettler-Toledo company (Switzerland).

This team consists of experts in the fields of mass, electrical, dimensional, and thermal metrology, visible and x-ray optics, surface physics, opto-electronics and opto-mechanics, precision electromagnetic engineering, mass spectrometry, modelling, and data analysis.

The discrepancy between the measured $h$ values indicates that an error was made in at least one experiment. Therefore, the project objective is to understand and to clear it up. It aims at defining and fine-tuning a methodology to study and to resolve this discrepancy, to perform crossed analyses of the watt-balance and $^{28}$Si experiments, to identify the critical aspects, and to look at hidden assumptions and/or phenomena which might not have been considered. Additionally, no measurement demonstrated the $2 \times 10^{-8}h$ uncertainty required to make the kilogram redefinition possible. Therefore, the project aims at increasing the measurement accuracy up to this level. Eventually, strategies to monitor the stability of the international prototype of the kilogram and of the kilogram realizations with reference to Si spheres will be designed.
Expected results and potential impact

Independent watt-balance measurements having at least $5 \times 10^{-9}/h$ uncertainty are expected. These measurement results are essential to study the discrepancy between the NIST and NRC watt balances.

The IAC determination of $N_A$ went near to the $2 \times 10^{-8}/h$ uncertainty target. The expected results are refinements of all the measurements and a repetition of the $N_A$ determination with the ambitious goal of a $1.5 \times 10^{-8}/N_A$ uncertainty. These stress tests are expected to bring into light mistakes or hidden assumptions, excluding or identifying and eliminating them.

To monitor the prototype and kilogram-realizations stability, proposals are to keep operational several watt balances, to monitor the $h/m_N$ ratio via stable mass references, and to use natural Si témoins whose mass evolution is determined by the same technologies developed to determine $N_A$. To achieve these goals, technologies and competences not yet available are necessary. Therefore, the project is expected to promote innovation, the development of measurement capabilities, the integration of the national research programmes, and to keep Europe in a top-level position in the framework of the international metrology.

State of the art

The figure 3 shows the LNE watt balance, whose foundations have been set within the EMRP project e-Mass. In summer 2012, the watt balance was operated in test mode. Static and dynamic measurements have been carried; $5 \times 10^5$ resolution and accuracy levels have been reached. In the same e-Mass framework, the EJPD-METAS completed a measurement having $3 \times 10^{-7}/h$ uncertainty, which revealed the ultimate limits of the technologies so far developed. Therefore, the EJPD-METAS started the realization of a new watt balance (Fig. 4), whose critical components have been redesigned. The EPFL-LSRO, CERN, and Mettler-Toledo support the design and characterization of the balance translation stage, magnetic circuit, and force cell. These components are under development and test.

The PTB re-determined $N_A$ after Cu and Ni decontamination of the surface of the IAC sphere AVO28-S8. The decontamination required wet etching and re-polishing. The sphere diameter and mass decreased by 300 nm and 9 mg, but the measured $N_A$ value agrees with the one previously determined. This result proves that the capability to predict the mass variation of a $^{28}$Si prototype of the kilogram is presently better than $5 \times 10^{-9}$ kg.

The roundness error of the $^{28}$Si spheres and the volume measurement are the major factors limiting the accuracy of the $N_A$ measurement. Therefore, IOM is focusing on ultra-precision ion-beam and plasma-jet machining of the $^{28}$Si sphere surface. Test natural Si spheres have been manufactured by the PTB (Fig. 5) with sub-nanometer surface roughness and 70 nm form error (to be compared with about 90 nm of the AVO28 S5 and S8 spheres). An additional sphere interferometer has been made operational at PTB, having larger etalon and etalon-sphere separations. The performance of both interferometers has been successfully checked by comparing the topographical surveys of the same test sphere.

The PTB repeated molar mass measurements by dissolving the Si28 samples in aqueous solutions of an hydroxide different from NaOH, as proposed by the NIST. Results are in agreement with the 2010-2011 data and with the molar-mass value measured by NIST. Investigations are under way to clarify the origin of the (small) discrepancy observed between the NIST/PTB and NRC measurement results.
The INRIM realized a new optical interferometer operating at 532 nm and coupled it to the x-ray interferometer. Measurement repetitions of the lattice parameter, by using both the old and new optical interferometers, excluded errors, at the present 3 nm/m accuracy.

Test measurements of Si purity by nuclear activation analysis were made at the TRIGA Mark II reactor of the Pavia university by using samples of the natural Si crystal WASO04 and of a contaminated Si28 crystal grown to verify the enrichment capability. For a number of elements the detection limits are still too high to exclude contamination at the 1 μg/g level. Solutions are under considerations: longer irradiation time and/or alternative, more powerful, neutron sources.

Surface characterization, volume, lattice parameter, mass, and molar mass measurements are performed in collaboration with the NMIJ. At the NMIJ, several new equipments have been installed to improve the topography of the crystal-lattice and the volume measurements; their performance is now under evaluation.

The collaboration with the BIPM is ensuring the link with the international prototype of the kilogram (IPK). An essential uncertainty contribution arises from the long-term drift of the BIPM working standards. In order to reduce this uncertainty contribution and to enable investigations of the stabilities of the IPK, watt balances, and 28Si spheres, the BIPM will carry out extraordinary calibrations of the BIPM working standards, watt balance mass standards, and 28Si spheres by using the IPK.
### JRP start date and duration:
01 September 2012, 3 years

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