Editorial

The general context of this special issue is the ongoing attempt to reform the International System of units (SI) with the ultimate goal of defining all units in terms of fundamental constants. Giving up the present definition of the mass unit defined by means of a unique material artefact, the international kilogram prototype, the trend is to define the mass unit by fixing the value of the Planck constant h . In the same way, the ampere, the kelvin and the mole would be redefined by fixing the elementary charge e , the Boltzmann constant k_B and the Avogadro constant N_A respectively. We thus expect that this volume will be also of benefit to anyone interested in the present discussion around the modernization of the SI.

As an introduction, the strong interplay between modern theoretical physics and metrology, sustained by continuously improving measurement results, is described. A better understanding of nature and of the universe, the quest for an improved quality of life through incessant technological progress as well as the need to establish trade and communication on a sound and equitable basis make metrology an essential science. At its fundamental level, metrology, one would say quantum metrology, aims at developing standards whose values refer directly to fundamental constants so that any quantity can be measured in unbiased natural units without referring to material artefacts. Consequently an important task of metrology is the determination of fundamental constants and, undoubtedly, a thorough test of the underlying theories.

As pointed out by Cohen-Tannoudji, there are at first four universal constants to be considered: the velocity of light in vacuum c , the gravitation constant G , the Planck constant h and the Boltzmann constant k_B . These constants are characterized by their ability to define the *horizon*, i.e. to reflect *fundamental limitation principles* and, consequently, a theoretical framework of reference based on a reliable metric can be established from quantum field theory, general relativity and quantum statistics. It is noteworthy that the three constants h , c and G are the building blocks of the units of mass, length and time in the well-known system of absolute units proposed by Planck. In addition to these four constants, various other fundamental constants intervene in the interpretation of quantum physics describing atomic as well as solid-state systems. Without classifying them in categories – as sometimes found in the literature – some of them are related to particular systems, as e.g. the Rydberg constant R_∞ , the quotient of the Planck constant and the relative atomic mass of cesium or rubidium $h/m_{Cs,Rb}$, the elementary charge e and the electron magnetic moment anomaly a_e . Others are dimensionless universal constants acting as fundamental parameters, such as the fine structure constant α or the electron mass to proton mass ratio m_P/m_e .

Thanks to the impressive development of cold atom physics, starting in the seventies by the original techniques of laser cooling, the improvement of trapping techniques developed earlier in the fifties on charged ions, and marked by a turning point in the nineties with the invention of the optical frequency comb, the determination of R_∞ , as well as the tests of the predictions of

Quantum Electrodynamics (QED) have been significantly improved by carrying out high precision hydrogen spectroscopy. The uncertainty associated with the values of R_∞ have decreased by more than four orders of magnitude over three decades, the lowest uncertainty reported so far being at the level of one part in 10^{14} . More recently, during the last decade, interferometry experiments using cold atoms of caesium or rubidium provide accurate measurements of the $h/m_{\text{Cs,Rb}}$ ratio. From this ratio, the value of the fine structure constant α can be deduced directly with an uncertainty approaching a few parts in 10^9 . This becomes competitive with respect to the uncertainty of the α value calculated from the most recent experimental value of the anomalous magnetic moment of the electron a_e using QED theory, and consequently, allows a stringent test of QED.

The great advances in cold atom physics are even more remarkable if their impacts in time and frequency metrology are considered. Microwave frequency standards such as caesium atomic fountains presently realize the SI second with, in the best case, an accuracy approaching one part in 10^{16} . An even better performance can be expected by moving to optical frequency standards. Two technologies are investigated, optical lattice clocks and optical clocks based on cold-trapped ions. The best results obtained so far show a reproducibility of a few parts in 10^{17} (from a comparison of two optical clocks based on single trapped Hg and Al ions) and an instability of $1 \cdot 10^{-16}$ for an averaging time of one hour. It is expected that in near future, the accuracy could reach the 10^{-18} range. In addition to the use of highly accurate frequency combs, this reproducibility is the result of an excellent mastery of experimental techniques which help to avoid or to reduce unwanted quantum effects (Doppler, Zeeman and Stark shifts, ...) and, thus, minimize the corresponding correction factors and the associated systematic uncertainties.

To complete these reviews on cold atom physics, related to the purpose of this topical issue, the Bose Einstein Condensate (BEC) and the applications of atomic clocks for fundamental tests are treated. Beside their likely metrological applications in atom interferometry, the observation of the BEC opens very interesting prospects in condensed matter physics, as shortly discussed below. Fountain clocks in space or optical clocks on earth are suitable tools to carry out precision tests in fundamental physics, general relativity and in astronomy. For example, the search for a possible drift of the fine structure constant and the measurement of Einstein's gravitational frequency shift are mentioned.

The importance of quantum electrical metrology has grown rapidly since 1990, following the recommendation of the Conference International des Poids et Mesures (CIPM) to implement the quantum Hall effect (QHE) and the Josephson effect (JE) as primary standards of resistance and voltage, respectively. These phenomena link the electrical quantities directly to h and e , through the von Klitzing constant R_K and the Josephson constant K_J , which are presumably equal to h/e^2 and $2e/h$, respectively. They insure a high level of reproducibility and a unique representation of the electrical units worldwide.

Compared to the performance of atomic clocks, the Josephson array voltage standards and the quantum Hall resistance standards reach a reproducibility of few parts in 10^{11} and parts in 10^9 respectively. But more direct comparisons of quantum voltage devices show remarkable agreements at a level of 10^{-16} and even 10^{-19} for the Josephson effect (10^{-10} and expected 10^{-11} in the near future for QHE devices). It is noteworthy that no correction factors intervene in these results. For this reason, even if it is not a final proof, the confidence is very high that the underlying Josephson and von Klitzing relations $R_K = h/e^2$ and $K_J = 2e/h$ are exact. The results also underline the fact that if correction factors exist, they would be of fundamental nature. The use of Superconducting Quantum Interference Devices (SQUID) and other marvellous instruments such as the Cryogenic Current Comparator (CCC) whose principle rests on the Meissner effect and Ampere's law, are at the origin of these very accurate measurements. It must be noted that similar to frequency combs, SQUIDs are suitable sensitive tools for astrophysics (far infrared and x ray spectroscopy) and for relativity (precision tests of the gravitation law), among numerous other areas in fundamental physics.

Through the development of highly accurate electromechanical systems such as the calculable capacitor, implementing a theorem discovered by Thompson and Lampard in electrostatics, or the watt balance, based on the equivalence principle between mechanical and electrical power,

the use of the Josephson array voltage standards (JAVS) and the quantum Hall resistance standards (QHRS) allows the determination of α and h .

Thanks to the great progress of nanofabrication in the eighties, a new class of quantum electric devices has emerged, the so-called Single Electron Tunnelling (SET) devices based on the Coulomb blockade. Similar to JAVS and QHRS, the SET devices could be the basis for a quantum current standard whose amplitude is equal to the product of the elementary charge and a frequency. The most promising candidates for the realization of a quantum current standard are found either in metallic systems (aluminium electron pump, semiconductor devices) or in superconducting systems (hybrid single electron transistor). The Coulomb blockade of the SET provides the third leg of the quantum metrological triangle (QMT). Its closure by applying Ohm's law to the quantities observed in JAVS, QHRS and SET devices, or by means of the electron counting capacitance standard (ECCS) is a great challenge. In addition, by combining the results from the watt balance, the calculable capacitor and a single-electron tunnelling experiment, the elementary charge e can be determined directly.

The development of micro and nano-devices has not only been of benefit for quantum electrical metrology but also for thermometry. Indeed, several secondary and primary thermometers for the cryogenic temperature scale have been developed. These include normal metal-insulator-superconductor tunnel junctions, Johnson noise thermometers coupled to a SQUID, shot noise and Coulomb blockade thermometers.

An important part of metrology is an appropriate assessment of the measurement uncertainty. This includes a realistic modelling of the measurement process and the knowledge of the noise processes involved. In this context, the investigation of serial correlations in observation data is absolutely necessary in a correct analysis of measurement results and particularly for validating that the calculation of the standard deviation of the mean from a series of data is relevant. Some methods are reviewed including the Allan variance, originally used in the time and frequency domain but now widely employed in various domains like quantum electrical metrology for example. Methods involving spectral analysis and autocorrelation functions are also described. In general, the "Guide to the expression of uncertainty in measurement", the so-called GUM (ISO standard 1995), is recommended for establishing any uncertainty budget. However, in some cases, the concept of the propagation of distributions is more appropriate with a numerically controlled implementation based on a Monte Carlo method. Prior to carry out such statistical analysis on experimental data, the noise properties of the measurement set-up and particularly of the device under test must be investigated, in order to optimise the accuracy of the measurement. As example, the quantum noise properties for general quantum conductors are reviewed, giving some examples of quantum suppression of shot noise (like in the quantum Hall effect regime) and details on low and high frequency measurement techniques very useful in quantum electrical metrology (resistance and low current measurements). On the other hand, the quantum shot noise can be exploited in temperature metrology to realise a primary thermometer.

The new developments bring cold atom physics and condensed matter physics closer together and open up new links between the time and frequency and the electricity and magnetism fields. At first the Bose-Einstein condensation (BEC), which is observed in an ensemble of ultra cold atoms when a critical value between the atomic density and the thermal de Broglie wavelength is reached, allows one to reproduce phenomena of condensed matter physics. The BEC can serve as a model and contribute to the understanding of phenomena such as superfluidity, the electron pairing in high-critical-temperature (HTc) superconductivity or the Anderson localization. Conversely, in solid state devices such as graphene, the relativistic behaviour of electrons is put forward to explain the observation of the anomalous quantum Hall effect. Another example is the development of superconducting quantum information circuits, *e.g.* based on the Cooper pair box, which may be used for the generation of quantum bits (qubits). These devices mimic the atom with two quantum levels and from which, among others, *e.g.* Rabi oscillations and the Stark effect can be observed.

The CODATA task group collects all the available published data on fundamental constants, then, using a least square adjustment (LSA) method, calculates the most probable values of the constants. In this framework, LSA values obtained from the two fields (cold atoms and solid

state) and from others can be compared. Validity tests can be performed, relaxing or not some constraints in the observational equations. For example, the exactness of the von Klitzing and Josephson relations $R_K = h/e^2$ and $K_J = 2e/h$ has been checked. For the von Klitzing relation, no significant deviation at a level of parts in 10^8 is observed between the values given on one hand by atomic physics measurements, *i.e.* measurements of a_e involving QED calculation and measurements of h/m ratios and calculable-capacitor based measurements of R_K provided by the QHE. The trickiest issue is the strong disagreement of one part in 10^6 between the values of h derived from watt balance and quantum voltage and resistance standards and the value of h deduced from the measurement of the molar volume of a silicon sphere $V_m(\text{Si})$. This problem needs to be solved with an agreement to be found at a level of one part in 10^8 to make a redefinition of the mass unit in terms of a fundamental constant (h for example) possible. By deleting the discrepant $V_m(\text{Si})$ value of h as well as those relating to gyromagnetic ratios from the whole set of data, the Josephson relation is found valid at the uncertainty level of several parts in 10^7 . An alternative of checking the validity of this relation is to close the quantum metrological triangle (QMT). Similarly, a validity test of the Einstein's energy-mass equivalence principle $E = mc^2$ was performed, showing no discrepancy at an uncertainty level of 4 parts in 10^7 .

This issue concludes by exposing the new paradigm in metrology for the future, intrinsically linked to a *quantum* SI. Thanks to the ongoing amazing progress of technology and the improved techniques available for understanding noise mechanisms, metrology is entering a new phase. The change has started by the possibility to manipulate ultra cold atoms to make quantum clocks. In electricity and magnetism, the measurement of macroscopic quantities such as the magnetic flux or the electromotive force and the current becomes detection and a control of single quantum of flux or charge respectively. In near future, the luminous intensity will be traced back to the SI by detecting single photons. By extension, any information flux is expected to be controlled at the quantum level through the manipulation of photons, electron charge, spin or quantum flux. Sooner or later, this long evolution of metrology needs the implementation of a new SI, well matched with the present knowledge of physics. It must be noted that a similar evolution occurs in the scope of another emerging branch of modern metrology, called nanometrology, to face up issues with respect to nanosciences and nanotechnologies. Measurands (*i.e.* the most relevant quantity to be measured), which are defined for macroscopic objects or systems may no longer be appropriate at the nano scale where surface and quantum effects become predominant.

We would like to conclude this editorial by reminding a message outlined by Cohen and Dumond in 1965, “*measurements of the physical constants to ever greater levels of accuracy are important /.../ because they may lead to the discovery of a previously unknown inconsistency or the removal of a known inconsistency in our physical description of nature*”. This point of view, in agreement with the more general principle that *experiments should be carried out even if there are no theoretical predictions*, can be extended to the improvement of the definition and realization of the SI units. These research activities on fundamental constants and standards need constant support to always provide “*the most consistent SI possible*” as usually recommended by the CIPM. Thus, this should permanently be kept in mind and used as a guiding principle for decision makers in metrological institutes and organisms.

We would like to express our gratitude to all contributors for providing up-to-date reviews and papers for this special issue – many of them subsequently fleshed-out tutorial reviews based on lectures given at a Les Houches school back in 2007, which have been completed by separate submissions. We further thank the referees for having contributed to the overall effort of making this special issue a reference publication in the field.

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