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Mise en pratique of the new kelvin using Doppler Broadening Thermometry with a direct link to the primary frequency standards

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Abstract— We aim to demonstrate the first *mise en pratique* of the kelvin, within the framework of the new International System of Units (SI), with a direct link to the atomic fountains of LNE-SYRTE laboratory, the French time-frequency metrology institute. The Boltzmann constant being fixed in the new SI, the *mise en pratique* of the kelvin can be cast as a frequency measurement. One method considered, Doppler Broadening thermometry (DBT), originally proposed and initially demonstrated at Laboratoire de Physique des Lasers is being developed by us and others. We report our recent efforts towards implementing DBT with a direct link to the primary frequency standard in the 300-430K range to demonstrate its potential.

Keywords— *new international System of Units, temperature unit, mise en pratique of the kelvin, Doppler broadening thermometry, high-resolution molecular spectroscopy, optical frequency link*

I. INTRODUCTION

In 2019, the new International System of Units (SI) came into effect and several projects are under way to prepare new *misés en pratique* of base units. We aim to demonstrate the first *mise en pratique* of the new kelvin with a direct link to the primary frequency standards of LNE-SYRTE laboratory, the French time-frequency metrology institute. The Boltzmann constant k being fixed in the new SI, the *mise en pratique* of the kelvin can be cast as a frequency measurement. It is not any more based on the triple point of water macroscopic artefact. The method considered here, Doppler Broadening Thermometry (DBT), was originally proposed and demonstrated by us at Laboratoire de Physique des Lasers (LPL) [1], and is currently being developed by us and others [2, 3].

II. PRINCIPLE OF DOPPLER BROADENING THERMOMETRY

DBT consists in measuring the Doppler broadening of a molecular or atomic absorption line of a gas at thermodynamic equilibrium. The Doppler-broadened profile reflects the Maxwell-Boltzmann velocity distribution of gas particles. In conjunction with some highly accurate modelling of the line profile, it is possible to use the data to

retrieve the e -fold half-Doppler width Δ_{VD} , whose relation to the temperature T of the gas is given by:

$$T = (m c^2 / 2 k) (\Delta_{VD} / \nu_0)^2 \quad (1)$$

where m is the molecular mass, ν_0 the central frequency of the molecular line and c is the speed of light. The present project hinges on the LPL experiment initially dedicated to the measurement of k by laser spectroscopy developed for about a decade that allowed us to determine k with a combined uncertainty of 50 ppm [1, 4-15]. It consists in precisely recording the profile of an absorption line of gaseous ammonia at thermal equilibrium.

III. THE SPECTROMETER

The spectrometer is based on the secondary frequency standard of the mid-infrared spectral region emitting around 10 μm , a CO₂ laser stabilized on a saturated absorption line of OsO₄. It exhibits a sub-Hz accuracy, a frequency instability of 0.1 Hz for a 100 s integration time and an emission line width smaller than 10 Hz [16]. Broad frequency tunability is achieved by coupling the CO₂ laser to a microwave electro-optic modulator (EOM) which generates two sidebands tunable from 8 to 18 GHz on each side of the fixed CO₂ laser frequency [1]. To increase the laser power available for spectroscopy a 10.3 μm , a continuous wave near-room-temperature single-mode distributed feedback (DFB) quantum cascade laser (QCL) is coherently phase-locked to one of the two tunable sidebands. The stability and accuracy of the OsO₄/CO₂ laser frequency standard are transferred to the QCL resulting in a line width narrowed by about four orders of magnitude with respect to free-running conditions [12].

IV. TRACEABILITY TO THE PRIMARY FREQUENCY STANDARDS

To ensure traceability to the primary frequency standards, we have developed a method to calibrate the absolute frequency of our secondary mid-infrared frequency standard to the LNE-SYRTE Cs fountain clocks which realize the SI standard of frequency [16-18]. Sum-frequency generation in a AgGaSe₂ non-linear crystal is used to measure a beat-note signal between the CO₂ laser and a near-infrared frequency comb which is itself locked to an ultra-stable 1.5 μm laser signal located at LNE-SYRTE laboratory. This signal is calibrated there to the primary frequency standards. The frequency reference is transferred to LPL using a fibre optical link with active compensation of the propagation-induced phase noise [19].

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V. RESULTS AND PERSPECTIVES

We report preliminary DBT ammonia spectra with direct link to the primary frequency standard in the 300-430K range to demonstrate its potential and study its limitations. For validation of our implementation of the new kelvin, comparison to the former realization of the temperature unit, the International Temperature Scale of 1990 (ITS-90), is indispensable. To ensure traceability to ITS-90, spectroscopy is performed in an absorption cell placed inside a ITS-90 temperature controlled thermostat consisting of a copper thermal shield itself inside a vacuum chamber [5, 9]. A heating system based on resistive wires wrapped around the enclosure allows the temperature to be varied in the desired range. The cell temperature is measured with ITS-90 calibrated glass capsule standard platinum resistance thermometers. Special attention is paid to reduce temperature gradients and to improve the long-term temperature stability of the set-up. Our preliminary data show that a measurement of the thermodynamic temperature with an uncertainty at the 50 ppm level (20 mK at 400 K), already demonstrated with our measurement of k [6, 9, 14, 15], is reachable with ~ 1000 ammonia spectra corresponding to a few-days run. Our longer term target uncertainty is 10 ppm, level at which DBT will have to be compared to other implementations of the new kelvin such as acoustic gas thermometry, Johnson noise thermometry, or dielectric constant gas thermometry.

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