European Partnership on Metrology
Call 2023 –Fundamental Metrology, Industry, Normative and Research Potential

Selected Research Topic number: **SRT-f04**
Version: 1.0

Title: Fundamental physical metrology with cold molecules

Abstract

Recent experiments have demonstrated the tremendous potential of frequency metrology of cold and precisely controlled gas-phase molecules for improved determination of fundamental constants, tests of their constancy over time, as well as tests of aspects of the Standard Model, including its possible extensions. Upgrades to these experiments are advised, as these may also lead to new standards and techniques that help maintain and expand the leading role of European metrology in the world. Conversely, the upgraded experiments are in urgent need of (remote) comparisons with frequency standards at NMIs, which could be achieved by employing the recently developed infrastructure and methods for fibre-optic frequency transfer.

Keywords

Frequency metrology; fundamental constants; symmetry laws; cold molecules; molecular ions; cold matter; precision measurements; infrared frequency standards; SI-traceable frequency dissemination; optical fibre link

Background to the Metrological Challenges

There is a need for good frequency standards in the infrared for a range of precise spectroscopic measurements in a variety of molecules to allow advances in fundamental physics and physical chemistry. Such standards have the potential to improve tests of fundamental symmetries and postulates of quantum mechanics, to explore limits of quantum interference and mechanisms of decoherence, to measure either absolute values of fundamental constants (proton- and deuteron-to-electron mass ratios, m_p/m_e and m_d/m_e, Rydberg constant, charge radii), or their variation in time (fine structure constant, m_p/m_e), to provide stringent tests of quantum electrodynamics and to search for physics beyond the standard model by looking for fifth forces and extra dimensions at the molecular scale or signatures of dark matter. Various species of ultracold molecules can be formed by starting with ultracold atomic mixtures through a two-step process: Magneto-association of atom pairs into weakly-bound dimers near a Fano-Feshbach resonance, followed by coherent optical transfer onto deeply-bound states via stimulated Raman adiabatic passage.

At present only three absorption lines in the infrared region (CH_4 at 3.39 µm, OsO_4 at 10.3 µm, C_2H_2 at 1.54 µm) are recommended as secondary frequency standards by the BIPM (Bureau International des Poids et Mesures). The cooling and trapping of a variety of molecules, especially metal hydrides, halogens and complex molecules, requires high density beams of pre-cooled molecules. Current techniques suffer from low density, are often pulsed, and have not been extended to the production of complex polyatomic molecules. These sources are often a bottleneck to improve the precision of frequency measurements. To address these shortcomings, there is thus a need to develop high-flux molecular beam sources, novel methods of laser cooling and sympathetic cooling to the ground state of motion, methods to produce molecular fountains, quantum logic spectroscopy of molecular ions, stable mid-infrared laser sources, frequency combs with extended spectral range and SI-traceability. These developments could use the existing network of optical fibre links that has recently been developed in Europe to connect many labs and NMIs together. In addition, the comparison protocols, which have been developed for atomic clocks, could be extended. There is also a need to reduce the uncertainty of fundamental constants and to determine whether they vary in time or space, since metrology is based on these constants and their stability.

A large number of molecular transitions have been proposed for precise tests of fundamental physics. However, these transitions and their systematic shifts are often derived from existing, low precision data or molecular structure calculations. While these techniques are important tools to find the most promising molecular species and transitions, the available information is often insufficient and requires experimental verification and characterisation. Moreover, the sensitivity of these transitions to electric fields, magnetic fields, temperature, and to laser field intensity, needs to be assessed experimentally.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on frequency metrology research of cold controlled gas-phase molecules necessary to improve determination of fundamental constants.

The specific objectives are

1. To develop a frequency standard based on ultracold molecules, in the mid-infrared with a linewidth below 10 Hz, stability of 2×10^{-15} at 1 s, and the potential to measure the stability of the electron-to-proton mass ratio to a fractional precision better than 10^{-17} per year.
2. To develop metrology-grade highly stable, SI-traceable and widely tuneable laser sources in new and extended regions of the mid-infrared. The stability should be 10^{-15} or better, the tuning range should be tens of GHz, corresponding to the typical spectral window of distributed-feedback mid-infrared quantum cascade lasers.
3. To develop ultra-high-resolution spectrometers from the microwave to the UV spectral window, with accuracies ranging from 10^{-12} to 10^{-15} in the mid-infrared, based on efficient and continuous sources of buffer gas-cooled molecules, in particular metal hydrides and metal halogens, and complex molecules. These should be probed using sub-Doppler spectroscopy and Ramsey interferometry, and the SI-traceable ultra-stable sources developed in objective 2 and should be used as frequency standards.
4. To improve the determination of fundamental constants, such as the proton-to-electron and the deuteron-to-electron mass ratios, the Rydberg constant and charge radii of simple nuclei, by performing high resolution spectroscopy on state selected ultracold molecules and/or molecular ions, using simple and calculable species, including Rydberg molecules.
5. To facilitate the technology transfer by the European research community working on infrastructures and methods by creating a coordinated and optimised strategy for the long-term development of a framework allowing simultaneous, and potentially synchronised, SI-traceable frequency measurements on different molecular systems, at different locations in Europe.

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,

- Facilitate improved industrial capability or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the high precision frequency sector.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of the Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Time-scale

The project should be of up to 3 years duration.