Towards Molecular Hg_2 Clock for Testing Fundamental Physics

M. Witkowski*, R. Ciuryło, A. Linek, R. Munoz Rodriguez, M. Zawada
Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University
Toruń
*e-mail: marcin_w@umk.pl

We present the development of a new molecular sensor for fundamental interactions' studies based on clock transitions in a Hg-Hg system. The study planned in our project will enable implementing optical Feshbach resonances in systems like Hg_2 or Hg-alkali atoms for quantum engineering purposes and establish the basis for the construction of the Hg_2 optical molecular clock [1, 2]. This new tool will push limits for fundamental research by orders of magnitude.

Keywords: Hg, mercury, molecular clock, ultra-cold molecules, fundamental physics

I. Introduction

The energetic structure of a molecule is determined by interactions between its components and their quantum mechanical dynamics. It involves mainly the electromagnetic interaction between atomic nuclei and electrons, and their relativistic dynamics. Other interactions - more exotic for molecular physics - such as strong nuclear interactions affect the molecular structure by shaping atomic nuclei [3]. The molecule's energetic structure is also affected by interactions with the environment. For example, even in an isolated molecule, the energy levels in empty space are shifted by the interaction with the electromagnetic field of vacuum [4]. This intrinsic sensitivity of molecular structure to interactions and coupling with the environment makes them attractive as sensors of new interactions or objects not yet included in the Standard Model [5]. Nowadays, the possible sensitivity of atomic structure to various factors [6, 7] is explored, for instance, in laboratory searches for dark matter [8] by the global observatory [9] of optical atomic clocks [10] or in the global network [11] of optical magnetometers [12]. Our project takes advantage of simple two-atom molecules with relatively heavy nuclei, which gives a unique opportunity to look for unexplored yet hadron-hadron interactions at nanometre scale. New interactions can be seen as the fifth force or the non-Newtonian gravitational interaction.

II. METHODS/RESULTS

For the experimental realization of the search of new hadron-hadron interactions, one of the heaviest two-atom molecules, Hg_2, will be used. Interatomic Hg-Hg potential is relatively well known [13] compared to other heavy molecules like Yb_2. Nevertheless, to reduce the influence of imperfections of theoretical description, we will take advantage of quantum defect theory [14] and measure rovibronic bound states in the ground electronic configuration near the dissociation threshold [15]. This approach has been recently proposed as a promising tool for searching new interactions [16].

Spectroscopy of Hg_2 will be carried out with gas samples cooled to microkelvin temperatures in a dipole trap. Experimental results of one- and two-colour photoassociations for a broad range of isotopologues of Hg_2 will provide necessary information about quantum defects describing near-threshold bound states with and without the electron excitation. Mapping bound states in the Hg_2 system allows choosing a proper isotopologue to realize the optical molecular clock [16]. To achieve the electronic ground state of Hg_2, the two-stage experiment will be performed. At first, a weakly bound state of the Hg_2^* molecule (close to its dissociation limit) will be created by photoassociation. Then the electronic ground-state molecule will be formed via stimulated Raman adiabatic passage (STIRAP). The experimental attempt to realize an optical molecular clock will be based on possible scenarios proposed in Ref. [1]. The photoassociation spectra will be referenced to optical atomic frequency standards and should reach a sub-kHz level of accuracy. The formation of ultracold Hg_2 molecules by photoassociation will make a significant step towards a better understanding of fundamental physics.

Acknowledgments

The "A next-generation worldwide quantum sensor network with optical atomic clocks" project (TEAM/2017-4/42) is carried out within the TEAM IV Programme of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund.
This project 20FUN01 TSCAC has received funding from the EMPIR programme co-financed by the Participating States

and from the European Union's Horizon 2020 research and innovation programme.
The project is supported by the National Science Centre, Poland, under OPUS programme no. 2021/41/B/ST2/00681. The measurements are performed at the National Laboratory FAMO (KL FAMO) in Toruń, Poland, and are supported by a subsidy from the Polish Ministry of Science and Higher Education.

REFERENCES

[1] M. Borkowski, "Optical Lattice Clocks with Weakly Bound Molecules", Phys. Rev. Lett. 120, 083202 (2018).

[2] S. S. Kondov, C. H. Lee, K. H. Leung, C. Liedl, I. Majewska, R. Moszynski, T. Zelevinsky, "Molecular lattice clock with long vibrational coherence", Nature Physics, (2019).

[3] J. Schlembach, E. Tiemann. "Isotopic field shift of the rotational energy of the Pb-chalcogenides and Tl-halides", Chem. Phys. 68, 21-28 (1982).

[4] J. Komasa, K. Piszczatowski, G. Łyach, M. Przybytek, B. Jeziorski, K. Pachucki, "Quantum Electrodynamics Effects in Rovibrational Spectra of Molecular Hydrogen", J. Chem. Theory Comput. 7, 3105–3115 (2011).

[5] M. S. Safronova, D. Budker, D. DeMille, D. F. Jackson Kimball, A. Derevianko, C. W. Clark, "Search for new physics with atoms and molecules", Rev. Mod. Phys., 90, 025008-106 (2018).

[6] A. Derevianko, M. Pospelov, "Hunting for topological dark matter with atomic clocks", Nat. Phys. 10, 933–936 (2014).

[7] Y. V. Stadnik, V. V. Flambaum, "Improved limits on interactions of low-mass spin-0 dark matter from atomic clock spectroscopy", Phys. Rev. A 94, 022111-5 (2016).

[8] P. Wcisło, P. Morzyński, M. Bober, A. Cygan, D. Lisak, R. Ciuryło, M. Zawada, "Experimental constraint on dark matter detection with optical atomic clocks", Nat. Astron. 1, 0009-6 (2016).

[9] P. Wcisło, P. Ablewski, K. Beloy, S. Bilicki, M. Bober, R. Brown, R. Fasano, R. Ciuryło, H. Hachisu, T. Ido, J. Lodewyck, A. Ludlow, W. McGrew, P. Morzyński, D. Nicolodi, M. Schioppo, M. Sekido, R. Le Targat, P. Wolf, X. Zhang, B. Zjawin, M. Zawada, "New bounds on dark matter coupling from a global network of optical atomic clocks", Sci. Adv. 4, eaau4869-7 (2018).

[10] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, P. O. Schmidt, "Optical atomic clocks", Rev. Mod. Phys. 87, 637-701 (2015).

[11] S. Pustelny, D. F. J. Kimball, C. Pankow, M. P. Ledbetter, P. Wlodarczyk, P. Wcislo, M. Pospelov, J. R. Smith, J. Read, W. Gawlik, D. Budker, "The Global Network of Optical Magnetometers for Exotic physics (GNOME): A novel scheme to search for physics beyond the Standard Model", Ann. Phys. 525, 659–670 (2013).

[12] D. Budker, W. Gawlik, D. F. Kimball, S. M. Rochester, V. V. Yashchuk, A. Weis, "Resonant nonlinear magneto-optical effects in atoms", Rev. Mod. Phys. 74, 1153-1201 (2002).

[13] M. Krośnicki, M. Strojecki, T. Urbańczyk, A. Pashov, J. Koperski, "Interatomic potentials of the heavy van der Waals dimer Hg_2: A "test-bed" for theory-to-experiment agreement", Phys. Rep. 591, 1-31 (2015).

[14] F. H. Mies, "A multichannel quantum defect analysis off diatomic predissociation and inelastic atomic scatering", J. Chem. Phys. 80, 2514-2525 (1984).

[15] M. Kitagawa, K. Enomoto, K. Kasa, Y. Takahashi, R. Ciuryło, P. Naidon, P. S. Julienne, "Two-color photoassociation spectroscopy of ytterbium atoms and the precise determinations of s-wave scattering lengths", Phys. Rev. A 77, 012719-8 (2008).

[16] M. Borkowski, A. A. Buchachenko, R. Ciuryło, P. S. Julienne , H. Yamada, Y. Kikuchi, Y. Takasu, Y. Takahashi, "Weakly bound molecules as sensors of new gravitylike forces", Sci. Rep. 9, 14807-7 (2019).