1 PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan, all in English)

Project title:

Fundamental study of interactions between hadrons using optical Feshbach resonanses in ultra-cold mercury atoms.

1.1 Project goals

- **Building spectrometer for photoassociation spectroscopy.**
- **Performing photoassociation spectroscopy.**
- **Search for new physics in Hg_2 molecule.**

1.2 Outline

This project is devoted to the development of new molecular sensor to allow the study of fundamental interactions. The energetic structure of molecules is determined by the interaction between their components and the surrounding space. Therefore molecules can be used to look for exotic interactions like: hadron-hadron fifth forces [Fayet1996, Adelberger2009, Knapen2017], short range non-Newtonian gravitation [Fayet1996, Adelberger2009] or perturbations by dark matter fields [Derevianko2014], [Stadnik2016], [Wcislo2016], [Wcislo2018D2]. We will use isotopologues of the heavy Hg_2 molecules to look for signatures of additional interactions beyond the Standard Model [Safronova2018], [Salumbides2013]. at the nano-scale or at least to give new bounds for their possible magnitude. Our approach relies on confrontation of accurate spectroscopic measurements with theoretical calculations. If it reveals any statistically meaningful discrepancies we will provide new information related to isotopic variation of interatomic interactions and then we will look for signatures of exotic hadron-hadron interactions [Borkowski2019]. For this propose we will measure near-threshold bound states of the Hg2 molecule. In this case we will take advantage from relatively simple dispersion form of long range part of interaction potential supporting these states. Such approach reduces the influence of any inaccuracies in the description of the short range part of the potential on the sensitivity of the comparison of theoretical and experimental spectra to additional interactions.

The spectroscopy of Hg_2 will be carried out with gas samples in a dipole trap cooled to microkelvin temperatures. For this propose the existing experimental system for trapping and cooling Hg atoms [Witkowski2017] will be modified. Ultraviolet photoassociation spectroscopy will be performed for the first time to study near threshold bound states of Hg_2. The photoassociation resonances can be also seen as an optical Feshbach resonances which can be used to control interaction between atoms [Ciurylo2005]. They also will be used to explore possibility of realization of optical Hg_2 clock [Borkowski2018]. Spectra will be referenced to atomic frequency standards [Ludlow2015], [Morzynski2015] and should reach sub-kHz level of accuracy. Obtained in this way experimental energies of ro-vibronic states will be compared with ab initio based calculations [Borkowski2017Yb]. The atomic interactions will be modeled using an ab initio based mass-scaled Born-Oppenheimer potential improved by adding beyond-Born-Oppenheimer (BBO) adiabatic corrections and by partially treating the nonadiabatic effects using distance-dependent reduced masses. Finally the spectroscopic accuracy of calculations will be reached thanks to fitting of quantum defect and long-range van der Waals parameters.

We will also look for new possibilities to work on fundamental interactions between hadrons in case when antiproton is present in the atomic system. It will be possible thanks to participation in AEgIS/CERN experiment [Amsler2021].

Our work on ultra-cold Hg_2 molecules will provide not known up to now values of scattering lengths for different isotope combinations with very high accuracy. Such data are crucial for control of degenerated gases. Similarly, dispersion van der Waals coefficients will be determined with accuracy not reached before. Even more importantly the project will set experimental basis to construct an Hg_2 optical molecular clock, a new desired and powerful tool.

1.3 Work plan

1. Rearrangement of experimental system in KL FAMO for trapping Hg atoms in optical dipole trap.
2. Performing photoassociation spectroscopy in ultra-cold Hg atoms.
3. Determination of parameters describing interaction between Hg atoms like: scattering lengths and C_6 coefficients.

4 Confrontation of experimental spectra with at initio calculations and search for new interactions.
5 Exploration of new possibilities offered by ultra-cold atoms involving antimatter particles (antiprotons and positrons)
6 Participation in AEgIS/CERN experiment.

1.4 Literature

[Adelberger2009] E. G. Adelberger, et al., Prog. Part. Nucl.Phys. 62, 102–134 (2009).
[Amsler2021] C. Amsler, et al., Commun. Phys. 4, 19 (2021).
[Borkowski2017Yb] M. Borkowski, et al., Phys. Rev. A 96, 063405-10 (2017).
[Borkowski2018] M. Borkowski, Phys. Rev. Lett. 120, 083202 (2018).
[Borkowski2019] M. Borkowski, et al., Sci. Rep. 9, 14807-7 (2019).
[Ciurylo2005] R. Ciuryło, et al., Phys. Rev. A 71, 030701(R)-4 (2005).
[Derevianko2014] A. Derevianko, M. Pospelov, Nat. Phys. 10, 933–936 (2014).
[Fayet1996] P. Fayet, Class.Quant. Grav. 13, A19–A31 (1996).
[Knapen2017] S. Knapen, et al., Phys. Rev. D 96, 115021-26 (2017).
[Ludlow2015] A. D. Ludlow, et al., Rev. Mod. Phys. 87, 637-701 (2015).
[Morzynski2015] P. Morzyński, et al., Sci. Rep. 5, 17495-9 (2015).
[Safronova2018] M. S. Safronova, et al., Rev. Mod. Phys., 90, 025008-106 (2018).
[Salumbides2013] E. J. Salumbides, Phys. Rev. D, 87, 112008-8 (2013).
[Stadnik2016] Y. V. Stadnik, V. V. Flambaum, et al., Phys. Rev. A 94, 022111-5 (2016).
[Wcislo2016] P. Wcisło, et al., Nat. Astron. 1, 0009-6 (2016).
[Wcislo2018D2] P. Wcisło et al., J. Quant. Spectrosc. Radiat. Transfer 213, 41-51 (2018).
[Witkowski2017] M. Witkowski, et al., Opt. Express 25, 3165-3179 (2017).

1.5 Required initial knowledge and skills of the PhD candidate

1. An excellent academic record.
2. Good knowledge of quantum mechanics, atomic, molecular and optical physics.
3. Computer and experimental skills
4. It will be helpful if the master thesis has been done in atomic, molecular or optical physics.

1.6 Expected development of the PhD candidate's knowledge and skills

PhD student will get experiences in the following areas:
- work with ultra-cold atoms
- high resolution spectroscopy
- experimental vacuum and laser systems
- data analysis and confrontations of experimental data with ab initio calculations
- description of fundamental interactions including antimatter