

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

**Project title:** High-finesse cavity-enhanced cryogenic spectrometer for pushing the frontiers of molecular physics

### 1.1. Project goals

- Development of a high-finesse optical cavity operating at cryogenic temperatures
- Application of the cryogenic cavity to long-standing problems in molecular physics that are not accessible with conventional experimental technique, such as: accurate tests of QED for molecules, accurate tests of *ab initio* quantum-chemical calculations or providing reference cryogenic spectra for planetary studies

### 1.2. Outline

A typical approach to optical spectroscopy at cryogenic temperatures explored in recent decades was based on Fourier spectrometers [McKellar1990] (comparing to recent state-of-the-art methods, this approach is limited to medium resolution). In 2002, Morville et al. developed CRDS with a gas sample kept at temperatures down to 77 K (cavity mirror housings were kept at room temperature with heating tape) [Morville2002]. In 2006, Lewis et al. demonstrated operation of cryogenic (medium resolution) phase-shift cavity ring-down spectrometer [Lewis2006]. Very recently, a flow of cryogenic gas ( $T = 40$  K) through an optical cavity (the cavity mirrors were not cooled down) was maintained to carry out cavity ring-down spectroscopy [Wu2019]. The first Doppler-limited measurement of HD line was demonstrated at  $T=46$ K, but this setup has not reached yet the performance level allowing one to compete with the previous most accurate measurements of molecular hydrogen [Tao2018, Diouf2019, Zaborowski2020]. Within the proposed here project, we will develop an ultra-high finesse optical cavity that will be placed in the cryogenic vacuum chamber ( $T = 10$  K). We will also increase the intracavity power of laser light up to almost 10 kW. We will achieve it by developing a new high-power laser system. These two developments together will allow us to improve the previous best measurements [Tao2018, Diouf2019, Zaborowski2020] by two orders of magnitude and hence provide new stringent test of QED for molecules. The planned here development of the experimental setup will allow us to address several long-standing problems in molecular physics:

- The most accurate tests of QED for molecules and searching for new physics based on accurate measurements of rovibrational structure of simple molecules
- Accurate tests of *ab initio* quantum-chemical calculations – bound states of molecular complexes
- Accurate tests of *ab initio* quantum-chemical calculations – scattering states of molecular complexes at low temperatures and molecule-complex collisions
- Reference cryogenic spectra for planetary studies
- Collision-induced absorption (CIA) at cryogenic temperatures

Within this PhD project proposal, besides the development of the cryogenic spectrometer, at least one of the above mentioned scientific goals will be addressed (the choice depends on the experimental and technological circumstances and will be made after launching the spectrometer).

### **1.3. Work plan**

- Development of high-finesse cryogenic optical cavity
- Development of a room-temperature part of the optical setup
- Cryogenic spectra measurements
- Spectra interpretation and data analysis

### **1.4. Literature**

[McKellar1990] A. R. W. McKellar, J. Chem. Phys. 92, 3261 (1990)  
[Morville2002] J. Morville, et al., Chem. Phys. Lett. 363, 498 (2002)  
[Lewis2006] E.K. Lewis, et al., Rev. Sci. Instrum. 77, 073107 (2006)  
[Wu2019] H. Wu, et al., Optics Express 27, 37559 (2019)  
[Tao2018] L.-G. Tao, et al., Phys. Rev. Lett. 120, 153001 (2018)  
[Diouf2019] M. Diouf, et al., Opt. Lett. 44, 4733 (2019)  
[Zaborowski2020] M. Zaborowski, ..., P. Wcisło, Opt. Lett. 45, 1603 (2020)

### **1.5. Required initial knowledge and skills of the PhD candidate**

Skills and experience in experimental physics. Good knowledge of Matlab, LabView or Mathematica (or equivalent) software. Excellent problem-solving and communication skills. Written and verbal communication skills and presentation skills. Teamwork ability. Good command of the English language.

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

Knowledge, skills and experience in molecular and optical physics, laser and cryogenic technologies, and in molecular spectra analysis.