

## PHD PROJECT DESCRIPTION

(4000 characters max., including the aims and work plan to be published online)

**Project title:** Collision-induced quantum effects in spectra of atmospheric molecules

### 1.1. Project goals

Research on the Earth's atmosphere and climate change requires precise knowledge of quantum interactions between molecules and light in the presence of collisions. Under atmospheric conditions, molecular collisions significantly affect optical transition frequencies, complicating absorption spectra interpretation from satellite and ground-based instruments, while also providing additional information. These effects include line broadening, frequency shifts, changes in spectral shapes, and modifications of intensity distributions. Accurate understanding and modeling of these processes are essential for modern remote sensing systems developed by agencies such as NASA, ESA, and JAXA. Detecting greenhouse gas sources and sinks at global and local scales demands promille-level accuracy of line intensities and comprehensive collisional models, enabling reliable retrieval of molecular concentrations. Current reference data are often an order of magnitude less precise. High-accuracy studies of collisional effects are therefore crucial for interpreting spectroscopic measurements and for developing optical standards of gas concentration and temperature in line with the revised SI system.

### 1.2. Outline

The project focuses on laboratory measurements of line intensities, spectral shapes, and their temperature dependence for CO<sub>2</sub> and N<sub>2</sub>O bands near 1.6 μm. Key challenges include achieving promille-level uncertainty and characterizing speed- and temperature-dependent collisional effects. The cavity mode dispersion spectroscopy (CMDS) developed in our laboratory offers high dynamic range, resistance to detector nonlinearity, and direct frequency referencing. We plan to combine this high accuracy with broadband frequency-comb spectroscopy by developing a heterodyne cavity ring-down spectrometer (DC-CRDS) using an optical frequency comb. This will enable simultaneous measurement of absorption and dispersion for improved accuracy. The results will support atmospheric remote sensing, validation of ab initio models, and applications in optical gas metrology, in collaboration with international research groups. The project is supported by the NCN Opus grant, under which the PhD student can apply for an additional research scholarship.

### 1.3. Work plan

- Adaptation and testing of CRDS/CMDS spectrometer
- Spectral line shape fitting software development
- Measurement of greenhouse gases molecular spectra
- Spectral data analysis to retrieve line parameters and uncertainties
- Comparison of results with literature and requirements of various applications
- Presentation of the results, including papers and conference presentations
- PhD thesis preparation

### 1.4. Literature (max. 7 listed, as a suggestion for a PhD candidate preliminary study)

- D. A. Long, et al., *Frequency-stabilized cavity ring-down spectroscopy*, Chem. Phys. Lett. **536**, 1-8 (2012).
- J.-M. Hartmann, et al., *Recent advances in collisional effects on spectra of molecular gases and their practical consequences*, J. Quant. Spectrosc. Radiat. T. **213**, 178-227 (2018).
- Cygan, et al., *High-accuracy and wide dynamic range frequency-based dispersion spectroscopy in an optical cavity*, Opt. Express **27**, 21810-21821 (2019).
- D. Lisak, et al., *Dual-comb cavity ring-down spectroscopy*, Sci. Rep. **12**, 2377 (2022).
- K. Bielska, et al., *Subpromille measurements and calculations of CO (3–0) overtone line intensities*, Phys. Rev. Lett. **129**, 043002 (2022).
- A. Cygan, et al., *Dispersive heterodyne cavity ring-down spectroscopy exploiting eigenmode frequencies for high-fidelity measurements*, Science Advances **11**, eadp8556 (2025).
- W. Demtroder, “Laser Spectroscopy”, Springer 2008, DOI: 10.1007/978-3-540-73418-5

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

Knowledge of optics, spectroscopy, atomic and molecular physics. Good skills and experience in numerical methods and programming (preferred Labview, Mathematica, Fortran, Python). Mathematical skills in theoretical calculations. Experience in laboratory work is desirable, especially in building and using optical laser-based systems. Independence at work is welcome. High commitment to work and excellent problem-solving skills. Written and verbal communication and presentation skills (including English). Teamwork skills.

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

Knowledge, skills, and experience in laboratory work: building electro-optical systems (especially cavity-enhanced spectrometers), techniques of phase and intensity modulation of light, techniques of laser frequency stabilization, experimental techniques of molecular spectroscopy. Good knowledge of molecular spectroscopy, theoretical skills in description of interactions of light with molecules and with optical cavity. Skills in programming and numerical methods. Experience in finding solutions, making hypotheses and formulating final conclusions. Presentation skills, including research papers and conference presentations.