DOCTORAL PROJECT PROPOSAL
DOCTORAL SCHOOL OF EXACT AND NATURAL SCIENCES AST
NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ
Contest 007, May 2025

<table>
<tr><td colspan="3">Project discipline: physical sciences (nauki fizyczne)</td></tr>
<tr><td colspan="3">Project title (in English)</td></tr>
<tr><td colspan="3">Ultra-accurate laser spectroscopy for precision test of quantum electrodynamics for molecules</td></tr>
<tr><td colspan="3">Project title (in Polish)</td></tr>
<tr><td colspan="3">Ultradokładna spektroskopia laserowa do testowania elektrodynamiki kwantowej dla cząsteczek</td></tr>
<tr><td colspan="3">Project submitter(s)/Contact person</td></tr>
<tr><td rowspan="2">prof. dr hab. Piotr Wcisło
degree/title, first and last name</td><td colspan="2">piotr.wcislo@umk.pl 504 130 458
e-mail, phone number</td></tr>
<tr><td colspan="2">Institute of Physics, Nicolaus Copernicus University in Torun
organizational unit</td></tr>
<tr><td colspan="3">Suggested supervisors and mentors</td></tr>
<tr><td colspan="3">1) main supervisor*</td></tr>
<tr><td rowspan="3">prof. dr hab. Piotr Wcisło
degree/title, first and last name</td><td colspan="2">piotr.wcislo@umk.pl 504 130 458
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<tr><td>field:</td><td>Physics</td></tr>
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<tr><td colspan="3">2) co-supervisor*</td></tr>
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degree/title, first and last name</td><td colspan="2">.....
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organizational unit</td></tr>
<tr><td>field:</td><td></td></tr>
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<tr><td colspan="3">3) auxiliary supervisor*

A short justification for the need for auxiliary supervisor in this project</td></tr>
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degree/title, first and last name</td><td colspan="2">.....
e-mail, phone number</td></tr>
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*According to the Regulations of the Doctoral School of Nicolaus Copernicus University in Toruń (Resolution No. 30 of 23.04.2024), the scientific supervision of the preparation of the doctoral dissertation is provided **by the supervisor or supervisors OR the supervisor and the auxiliary supervisor**.
Meaning, you can provide the data of **a maximum of 2 people**: **2 co-supervisors OR the main supervisor and auxiliary supervisor.**

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

Project title: Ultra-accurate laser spectroscopy for precision test of quantum electrodynamics for molecules

1.1. Project goals

- Laser power saturation of the rovibrational transition in molecular hydrogen under cryogenic conditions
- Ultra-accurate experimental determination of the rovibrational energy in molecular hydrogen

1.2. Outline

Due to its simplicity, molecular hydrogen constitutes a perfect tool for testing fundamental physics: testing quantum electrodynamics [1], determining fundamental constants, or searching for new physics beyond the Standard Model. Molecular hydrogen has a huge advantage over the other simple calculable systems (such as H or He) of having a set of a few hundred ultralong living rovibrational states [2], which implies the ultimate limit for testing fundamental physics with molecular hydrogen at a relative accuracy level of 10^{-24}. The present experiments [3, 4] are far from exploring this huge potential. The main reason for this is that molecular hydrogen in its ground electronic state extremely weakly interacts with electric and magnetic fields; hence, molecular hydrogen is not amenable to standard techniques of molecule slowing, cooling, and trapping [5]. The main goal of this project is to further improve the present best accuracy by implementing for the first time the sub-Doppler saturation spectroscopy of molecular hydrogen in the deep cryogenic regime.

In this project, to reach the above goal, we will use the state-of-the-art experimental infrastructure that we have developed in my group, i.e., the spectrometer based on a high-finesse optical cavity cooled to a deep cryogenic regime [6, 7]. The experimental setup allows us to uniformly cool not only the sample but also the entire cavity, including the mirrors and cavity length actuator that ensures the thermodynamic equilibrium of a gas sample, which is critical for accurate measurements. We estimated that the accuracy in determination of molecular hydrogen rovibrational energies planned in projects will be better than 10^{-10}.

1.3. Work plan

- Development and preparation of the experimental system for saturating the rovibrational lines in hydrogen molecule
- Ultra-accurate measurements of the saturation sub-Doppler resonances in hydrogen molecule
- Experimental spectra analysis and data interpretation
- Analysis of the systematic and statistical uncertainties in the molecular hydrogen measurements

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

[1] M. Siłkowski, et al. Phys. Rev. A 107, 032807 (2023)
[2] L. Wolniewicz, et al., Astrophys. J. Suppl. S. 115, 293 (1998)
[3] M. Zaborowski, et al., Opt. Lett. 45, 1603–1606 (2020)
[4] M.L. Diouf, et al., Phys. Rev. Resear. 2, 023209 (2020)
[5] R. V. Krems, et al.,"Cold molecules – theory, experiments, applications", CRC press (2019)
[6] K. Stankiewicz et al., arXiv:2502.12703
[7] M. Słowiński, et al., Rev. Sci. Instrum. 93, 115003 (2022)

1.5. Required initial knowledge and skills of the PhD candidate

Skills and experience in experimental physics (in particular, in laser technologies). 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.

2. INFORMATION ON ACADEMIC ACHIEVEMENTS BY SUGGESTED PROJECT SUPERVISORS (REQUIRED FOR EACH PERSON INVOLVED)

A. Suggested supervisor	prof. dr hab. Piotr Wcisło degree/title, first and last name
a. Grants obtained in the last 5 years	
1.1 „Fundamental physical metrology with cold molecules", 2024 – 2027, grant europejski (w ramach propgramu European Partnership on Metrology), rola w projekcie: kierownik części UMK PROJEKT W TOKU REALIZACJI (data rozpoczęcia: lipiec 2024) 1.2. „Rozbudowa spektrometru laserowego ultrawysokiej rozdzielczości niezbędna do realizacji grantu ERC", 2023-2024, Duża infrastruktura badawcza MEiN (DEC 7448/IA/SP/2023), rola w projekcie: kierownik PROJEKT W TOKU REALIZACJI (data rozpoczęcia: wrzesień 2023) 1.3. "New experimental methods for trapping cold molecular hydrogen", 2023 - 2028, European Research Council, program ERC Starting Grant, (Prop. No. 101075678), rola w projekcie: kierownik i główny wykonawca	

PROJEKT W TOKU REALIZACJI (data rozpoczęcia: 1 sierpnia 2023)

1.4. “Advancing molecular collision studies to the limits of first-principles quantum calculations and accurate spectroscopy; novel approaches for providing reference spectroscopic data for studying planetary atmospheres”, 2023 - 2028, Narodowe Centrum Nauki, program SONATA BIS (2022/46/E/ST2/00282), rola w projekcie: kierownik i główny wykonawca
PROJEKT W TOKU REALIZACJI (data rozpoczęcia: 1 października 2023)

1.5. “Quantum scattering of optically excited oxygen molecules. From fundamental physics to atmospheric research”, 2022 - 2026, Narodowe Centrum Nauki, program PRELUDIUM BIS (2021/43/O/ST2/00211), rola w projekcie: kierownik i opiekun doktoranta
PROJEKT W TOKU REALIZACJI

b. H-index value	
according to Google Scholar	28
according to Scopus	25
c. Number of quotations	
according to Google Scholar	7524
according to Scopus	5985
d. Value of Field Weighted Citation Impact in the last 5 years (by SciVal database)	4.42

e. List of 4 major academic papers published or accepted for publication in the last 4 years, Ifs

1) Dispersive heterodyne cavity ring-down spectroscopy exploiting eigenmode frequencies for high-fidelity measurements,
A Cygan, S Wójtewicz, H Jóźwiak, G Kowzan, N Stolarczyk, K Bielska, **P Wcisło**, R Ciuryło, D Lisak,
Science Advances 11, eadp8556 (2025) (5-y IF = 13.7)

2) Accurate reference spectra of HD in an H2–He bath for planetary applications,
H Jóźwiak, N Stolarczyk, K Stankiewicz, M Zaborowski, D Lisak, S Wójtewicz, P Jankowski, K Patkowski, K Szalewicz, F Thibault, I E Gordon, **P Wcisło**
Astronomy & Astrophysics 687, A69 (2024) (5-y IF = 5.5)

3) Stimulated Raman scattering metrology of molecular hydrogen,
M Lamperti, L Rutkowski, D Ronchetti, D Gatti, R Gotti, G Cerullo, F Thibault, H Jóźwiak, S Wójtewicz, P Masłowski, **P Wcisło**, D Polli, M Marangoni
Communications Physics 6, 67 (2023) (2-y IF = 5.4)

4) Magic wavelength for a rovibrational transition in molecular hydrogen,
H Jóźwiak, **P Wcisło**
Scientific Reports 12, 14529 (2022) (5-y IF = 4.3)

f. List of promoted doctoral candidates: last names, titles of doctoral dissertations, names of universities, year and field of graduation

1. **Michał Słowiński**, title: "*Collisional effects in accurate rovibrational spectroscopy of simple diatomic molecules*", PhD in physics, graduated in 2022 at Nicolaus Copernicus University in Toruń
2. **Nikodem Stolarczyk**, title: *"Collison-induced line-shape effects in molecular spectra"*, PhD in physics, graduated in 2024 at Nicolaus Copernicus University in Toruń
3. **Hubert Jóźwiak**, title: *"Collisions of simple molecules and atoms in fundamental studies"*, defense day: May 9, 2025 (received 3 positive reviews), Nicolaus Copernicus University in Toruń

g. Information on currently supervised doctoral theses (list of doctoral students, name of the doctoral school, year of education, and topic of the doctoral dissertation, please indicated those on "the fifth year"- extension)

1. **Maciej Gancewski**, name of the doctoral school: Academia Scientiarum Thoruniensis, year of education: 3, and topic of the doctoral dissertation: "Quantum scattering of optically excited oxygen molecules. From Fundamental physics to atmospheric research.
2. **Kamil Stankiewicz**, name of the doctoral school: Academia Scientiarum Thoruniensis, year of education: 3, and topic of the doctoral dissertation: "High-finesse cavity-enhanced cryogenic spectrometer for pushing the frontiers of molecular physics"
3. **Bogdan Bednarski**, name of the doctoral school: Academia Scientiarum Thoruniensis, year of education: 3, and topic of the doctoral dissertation: "Accurate laser spectroscopy of simple diatomic molecules"
4. **Emha Riyadhul Jinan Alhadi**, name of the doctoral school: Academia Scientiarum Thoruniensis, year of education: 1, and topic of the doctoral dissertation: "Testing the quantum theory for molecules with ultra-accurate molecular beam spectroscopy"

h. Description of previous (and potential) scientific cooperation with other academic centers in the last 5 years (max. 1 page)

1. Dr. Franck Thibault, topic: *Quantum-scattering calculations*, **Institut de Physique de Rennes**, **Université de Rennes 1**, France (11 common articles, several visits in Rennes, 1 common grant)

2. Dr. Iouli Gordon, topic: *Spectroscopic databases*, **Harvard-Smithsonian Center for Astrophysics**, Cambridge, USA (5 common articles, 3 visits in Cambridge)

3. Dr. Ha Tran, topic: *Collisional line-shape effects*, **Laboratoirede Météorologie Dynamique/IPSL,CNRS, Ecole polytechnique, Sorbonne Université, Ecole Normale Supérieure**, Palaiseau, France (3 common articles, 1 visit in Paris)

4. Dr. Andrew Ludlow, topic: *Dark matter searches with optical atomic clocks*, **The National Institute of Standards and Technology**, Boulder,USA (1 common article, 1 visit at NIST Boulder)

5. Dr. Joseph T. Hodges, topic: *Molecular spectroscopy*, **The National Institute of Standards and Technology**, Gaithersburg, USA (2 common articles, 1 visit at NIST Gaithersburg)

6. Prof. Jun Ye, topic: *Cooling and trapping of polar molecules*, **Joint Institute for Laboratory Astrophysics (JILA), NIST + University of Colorado**, Boulder, USA (2 common articles in preparations, 2 visits at JILA)

7. Prof. Shuiming Hu, topic: *Molecular line-shape analysis*, **University of Science and Technology of China**, Hefei, China, (2 common articles, 1 visit in Hefei)

8. Prof. Krzysztof Pachucki, topic: *Rovibrational structure of hydrogen molecule*, **University of Warsaw**, Warsaw, Poland (1 common article, 2 visits in Warsaw)

9. Dr. Ruimin Guo, topic: *Cavity-enhanced spectroscopy*, **National Institute of Metrology**, Beijing, China, (1 common article, 1 visits at National Institute of Metrology in Beijing)

10. Dr. Alain Campargue, topic: *Collision sin molecular spectra*, **Université Grenoble Alpes**, Grenoble, France (3 common articles, 1 visit in Grenoble)

11. Prof. Wim Ubachs, topic: *Electronic structure of molecular hydrogen*, **Vrije Universiteit Amsterdam**, Netherlands, (1 common article, 2 visits at Vrije Universiteit Amsterdam)

12. Prof. Livio Gianfrani, topic: *Relativistic effects in molecular line shapes*, **Università degli studi della Campania**, Caserta, Italy (1 common article, 1 visits in Caserta)

13. Dr. Dionisio Bermejo, topic: *Rovibrational structure of hydrogen molecule*, **Instituto de Estructura de la Materia**, Madrid, Spain (2 common articles)

14. Prof. Marco Marangoni, topic: *Accurate spectroscopy o molecular hydrogen*, **Politecnico di Milano**, Milan, Italy (1 common article)

15. Prof. Konrad Patkowski, topic: *Ab inito calculations of molecular collisions*, **Auburn University**, Auburn, USA (2 common article)

i. Scientific resume of the supervisor (can be added as a separate file)

Added as a separate file.

4. DECLARATION OF TECHNICAL/EXPERIMENTAL/FINANCIAL RESOURCES SUFFICIENT AND NECESSARY TO COMPLETE THE PROJECT

I declare that I am able to provide the technical/equipmental support and financial resources necessary to carry out this doctoral project.

Toruń, 8.05.2025 signature of project submitter

I declare that I DO NOT HAVE financial resources for a doctoral scholarship as part of a project from external sources:……

project name/souces name

Toruń, 8.05.2025 signature of project submitter

5. DECLARATION CONCERNING THE AUTHORSHP OF PROJECT IDEA

I declare that the author of the idea for the doctoral project is: Piotr Wcisło

Toruń, 8.05.2025 signature of project submitter

6. DECLARATION CONCERNING CONSENT TO TRANSFER OF PROJECT SUPERVISION IF NEEDED

I declare that should the PhD candidate be accepted to the Doctoral School of Exact and Natural Sciences and started the project but for some reasons a change of the supervisor is necessary, **I AGREE/~~DO NOT AGREE~~** to transfer the substantive supervision of the project to another person designated by the Director of the Doctoral School of Exact and Natural Sciences of the Nicolaus Copernicus University in Toruń.

Toruń, 8.05.2025 signature of project submitter

7. DECLARATION CONCERNING THE POSSIBILITY OF PUBLISHING THE CONTENT OF THE PROJECT

I declare that the description of the project submitted to the contest from point 1 and basic scientific CV of a prospective supervisor, can be published on the website of Doctoral School of Exact and Natural Sciences, Nicolaus Copernicus University in Toruń.

Toruń, 8.05.2025 signature of project submitter