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

Project title: Superradiance with ultra-cold strontium atoms in high finesse cavity

1.1. Project goals

- experimental study of superradiance in ultra-cold strontium atoms on an ultra-narrow clock transition
- research toward the development of a continuous, active optical atomic clock using extremely narrow resonances (pioneering research on a global scale)
- fundamental physics studies, in particular cavity QED with ultra-cold atoms, and searching for new physics using optical atomic clocks

1.2. Outline

Superradiance on an ultra-narrow clock transition has only been demonstrated experimentally once [Nor16]. With our theoretical model, we were able to reproduce the results of that experiment [Gog20]. Utilizing the phenomenon of superradiance allows for the development of an active optical atomic clock [Bob22a, Bob22b]—a device with significant scientific potential. The active clock is a "high risk, very high gain" project. The doctoral research will involve work toward a continuous active optical atomic clock and its use in fundamental physics.

Optical atomic clocks [Lud15] are widely used in fundamental research, e.g., searching for dark matter [Wci18], variations in fundamental constants, testing the Standard Model, and more [Nar23]. Current optical clocks, despite their advantages, are limited by their architecture, and improving their performance by orders of magnitude seems technically impossible. An active optical atomic clock based on superradiance may solve this issue, enabling a major improvement in sensitivity.

The experimental setup for studying superradiance is also well suited for research in cavity QED, quantum systems, quantum metrology, many-body interactions, and quantum computing. A passive optical clock with cold strontium atoms will also be used during the project.

The National Laboratory for Atomic, Molecular and Optical Physics (KL FAMO) is the national consortium established at the Nicolaus Copernicus University (UMK) in Toruń, Poland for inter-university research. The main areas of research cover ultra-cold and degenerate matter, optical lattice atomic clocks, Bose-Einstein condensation, quantum states engineering, ion traps, ultra-cold molecules, cavity ring-down spectroscopy, and optical frequency combs. The Hz-level laser frequency control is also implemented for spectroscopic and metrological applications, and for new concepts of optical atomic clocks. Other key activities in KL FAMO are both experimental and theoretical studies of new physics beyond the Standard Model, in particular the search for transient indicators of hypothetical dark matter in the form of scalar fields or stable topological defects.

1.3. Work plan

- installation of high-Q cavity inside a vacuum setup, trapping atoms in crossed optical lattice (M1-M12)
- investigation on superradiance pulses, research with cold atoms strongly coupled with optical cavity mode (M12-M36)
- improvement of the setup with the goal towards sustained radiation and narrower linewidth (M12-40)
- use of the optical clocks and superrdaint setup for fundamnetal physics search (M6-M36)
- writing, submitting and defending the thesis (M36-M48)

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

[Bob22a] Bober M. and Bennetts S., Design of continuous mHz-line clock apparatus (2022), https://cordis.europa.eu/project/id/820404/results

[Bob22b] Bober M. and Bennetts S., Continuous mHez-line clock apparatus (2022), https://cordis.europa.eu/project/id/820404/results

[Gog20] Gogyan et al., Optics Express 28(5), 6881 (2020),

[Lud15] Ludlow A.D. et al., Rev. Mod. Phys. 87, 637 (2015),

[Nar23] Narożnik M. et al., Physics Letters B, 846, 138260 (2023),

[Nor16] Norcia M.A. et al., Sciectific Advaces 2, e1601231 (2016),

[Wci18] Wcisło P. et al., Science. Advance 4(12) aau4869 (2018).

1.5. Required initial knowledge and skills of the PhD candidate

- The applicant has to have finished a master degree within the last 4 years prior to recruitment in physics or a closely related field
- An excellent academic record.
- Experience through coursework and/or a research project in atomic and molecular physics
- Experience through coursework and/or a research project in quantum mechanics up to the second quantization.
- It is highly beneficial if the master thesis has been done in experimental atomic, molecular or optical physic

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

experience, knowledge and skills that are important in the high-tech industry and academia: experimental cold atoms, atom-light interaction, collective effects in quantum

gases, high resolution spectroscopy, laser physics and optics, ultra-high vacuum systems, electronics, programming and other