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

Project title: Fermionic molecular lattice clocks

1.1. Project goals

The goal of this combined theoretical and experimental project is to take significant steps towards the development of a fermionic molecular lattice clock at the National Laboratory FAMO in Toruń, Poland. Specific goals include:

1. to implement laser cooling and trapping of fermionic strontium atoms in the optical atomic clock at KL FAMO;
2. to observe photoassociation spectra in strontium-87;
3. to determine pathways towards production of ground-state weakly bound strontium-87 dimers;
4. to produce ground-state weakly bound strontium-87 dimers (stretch goal);
5. to observe an optical clock transition in strontium-87 molecules (stretch goal).

1.2. Outline

The Standard Model (SM) is the most successful physical theory to date. It is, however, incomplete: for instance, astronomical observations show that particles in the SM account only for about 16% of the total mass of the Universe. There are several theories that supplement the SM with new massive particles (e.g. relaxions) or propose the existence of compactified dimensions whose detectable side effect is the appearance of a new interatomic Yukawa-type force [1].

The recent developments in the fields of ultrastable lasers, optical frequency combs, laser cooling and quantum state control, and atomic optical clocks have put atomic, molecular and optical (AMO) physics at the forefront of measurement science. For this reason, a whole new field of tackling fundamental physics using tools of AMO physics have emerged [2]. In particular, **molecular lattice clocks** [3, 4] employing ultracold dimers comprising two spin-singlet bosonic atoms can serve as **sensitive quantum sensors for these new interactions**.

Here we propose to develop towards a **novel type of molecular lattice clock that employs dimers composed of two fermionic strontium atoms**. Strontium-87 is widely used in optical lattice clocks [5] and there are plans to implement this isotope in the clock setups at National Laboratory FAMO. A molecular lattice clock based on transitions in a $^{87}Sr_2$ strontium dimer could serve as a **novel detector of spin-dependent exotic interactions** [6]. In addition, strontium-87 could be used to perform the **first observation of an electronic molecular clock transition** [3], opening new opportunities in AMO physics and precision measurement sciences.

1.3. Work plan

The theoretical and experimental research will be conducted synergistically: experimental results will fuel theoretical calculations, theoretical results will guide experimental search. In addition, theoretical results can help the student have publications if experimental work is delayed due to unforeseen circumstances, reducing risk. It should be noted that completing even less than half of the envisioned tasks would already lead to publishable results.

Task ID	Description	Preceding tasks	Timeline	Comment
	Experimental tasks			
E-1	Implement laser cooling of ^{87}Sr in the KL FAMO optical clock	-	M1-M12	Stepping stone
E-2	Observe the ^{87}Sr atomic clock transition	-	M1-M12	Stepping stone

Task ID	Description	Preceding tasks	Timeline	Comment
E-3	Record ^{87}Sr photoassociation spectra using theoretical calculations as guide	T-2	M12-M24	Publishable result
E-4	Build a laser setup for photoassociation and photodissociation on the strontium intercombination line with phase locking to an optical frequency comb	-	M7-M18	Stepping stone
E-5	Use a known strontium-88 pathway to produce (photoassociate) and detect (photodissociate) cold strontium-88 molecules as a proof-of-concept	-	M12-M24	Stepping stone
E-6	Produce and detect strontium-87 molecules	E-1, E-5, T-2, T-3	M24-M36	Publishable result
E-7	Observe an optical molecular clock transition [3]	E-1, E-6, T-1	M37-M48	Publishable; groundbreaking result
	Theoretical tasks			
T-1	Determine the positions of molecular clock lines in $^{87}Sr_2$	-	M1-M24	Publishable result
T-2	Calculate preliminary theoretical photoassociation spectra for ^{87}Sr to guide experimental search	-	M1-M12	Stepping stone
T-3	Analyse strontium-87 photoassociation spectra using realistic potentials. Calculate pathways towards molecule production in the ground state	E-3	M13-M36	Publishable as proposal paper
T-4	Calculate the sensitivity of a strontium-87 molecular lattice clock to spin-dependent interactions [7]	-	M1-M24	Publishable as proposal paper

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

[1] B. Heacock, T. Fujiie, R. W. Haun, A. Henins, K. Hirota, T. Hosobata, M. G. Huber, M. Kitaguchi, D. A. Pushin, H. Shimizu, M. Takeda, R. Valdillez, Y. Yamagata, and A. R. Young, *Science* **373**, 1239 (2021).

[2] M. S. Safronova, D. Budker, D. Demille, D. F. Kimball, A. Derevianko, and C. W. Clark, *Reviews of Modern Physics* **90**, 025008 (2018).

[3] M. Borkowski, *Physical Review Letters* **120**, 083202 (2018).

[4] K. H. Leung, B. Iritani, E. Tiberi, I. Majewska, M. Borkowski, R. Moszynski, and T. Zelevinsky, *Phys. Rev. X* **13**, 011047 (2023).

[5] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, *Reviews of Modern Physics* **87**, 638 (2015).

[6] L. Cong, W. Ji, P. Fadeev, F. Ficek, M. Jiang, V. V. Flambaum, H. Guan, D. F. Jackson Kimball, M. G. Kozlov, Y. V. Stadnik, and D. Budker, *Rev. Mod. Phys.* **97**, 025005 (2025).

[7] M. Borkowski, A. A. Buchachenko, R. Ciurylo, P. S. Julienne, H. Yamada, Y. Kikuchi, Y. Takasu, and Y. Takahashi, *Scientific Reports* **9**, 14807 (2019).

1.5. Required initial knowledge and skills of the PhD candidate

- The applicant must have finished a master degree in physics or a closely related field within the last 4 years prior to recruitment;
- 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;

- It is highly beneficial if the master thesis has been done in experimental atomic, molecular or optical physics.

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

The PhD candidate will acquire critical skills for the upcoming quantum revolution in the high-tech industry:

- experimental cold atoms,
- atom-light interaction,
- high resolution spectroscopy,
- molecular physics,
- precision metrology,
- laser physics and optics,
- ultra-high vacuum systems,
- electronics,
- programming,

and others. In addition, the research is at the forefront of precision measurement sciences and AMO physics, and the completion of this research project could allow the PhD student to continue a research career as a postdoc at internationally recognized institutions.