Realizing quantum degenerate Bose-Fermi mixtures in an optical lattice

The experiment

The goal of the experiment is to create quantum degenerate gases of polar open shell ultracold molecules in an optical lattice. In contrast to alkali dimers, RbSr has three valence electrons, one of which is unpaired in the molecular ground state. This endows RbSr with a magnetic dipole moment in addition to the electronic dipole moment also available in alkali dimers. These magnetic and electric dipole momenta are two handles with which we can control the molecules and create interesting few -and many-body systems beyond the reach of atoms.

Nature of the master thesis

You will be part of the team, performing the experimental work on the Rb-Sr machine in a daily basis. You will be performing all the laser cooling, optical trapping of cold atoms and cooling on a day-to-day basis for realizing quantum degenerate gases of rubidium and strontium atoms.

You will be trained in:

- Optics and laser systems for cooling and trapping of atoms
- Experimental control systems and necessary electronics
- Optical lattices setups for quantum gases
- The physics of ultracold Bose-Fermi mixtures

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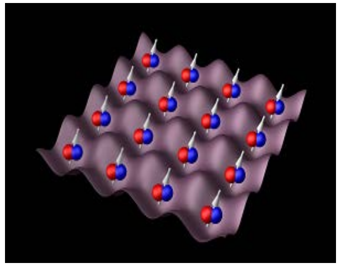
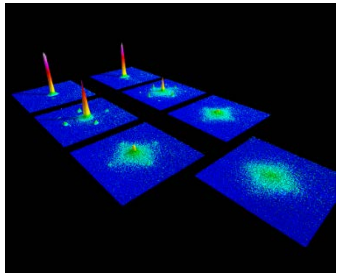
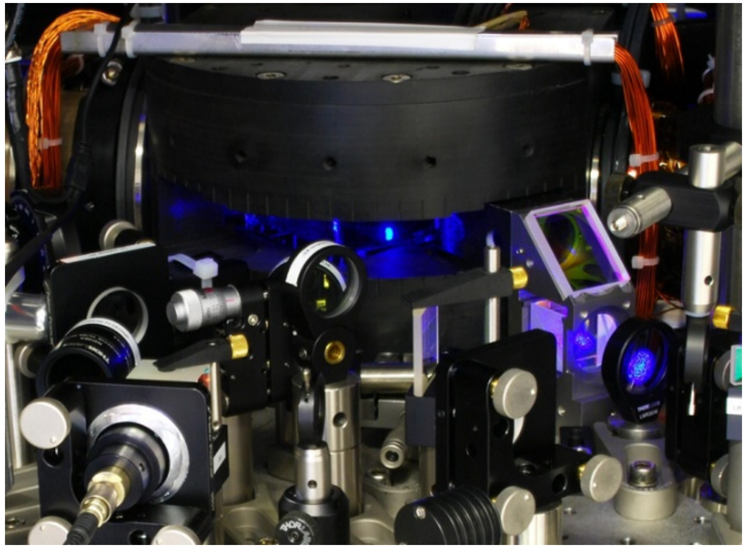
The master project

Realizing a quantum degenerate mixture of two atomic species relies heavily on the inter/intra species scattering lengths. In the case of ^{87}Rb (a boson) and ^{87}Sr (a fermion), the interspecies scattering length is very high, leading to losses by collisions. You will use a combination of novel techniques employing individual optical traps, adiabatic merging the ultracold clouds and exploiting an interspecies Feshbach resonance to tune the scattering length for Rb-Sr collisions. You will characterise the system and look at the possibilities of this ultracold mixture in an optical lattice towards quantum simulations.





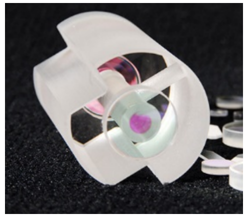


References

1. Observation of Feshbach resonances between alkali and closed-shell atoms, Nature Physics **14**, 881 (2018)
2. The RbSr $^2\Sigma^+$ ground state investigated via spectroscopy of hot & ultracold molecules, Phys. Chem. Chem. Phys. 20, 26221 (2018)
3. Quantum many-body dynamics of coupled double-well superlattices, Phys. Rev. A 78, 012330 (2008).
4. Many-body physics with ultracold gases, Rev. Mod. Phys. 80, 885 (2008).

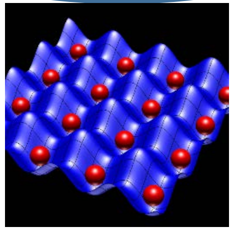
Building an optical lattice clock

Oscillator



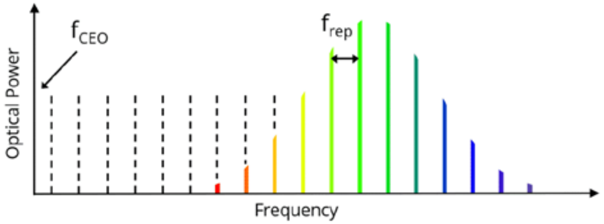
ULE cavity

Reference



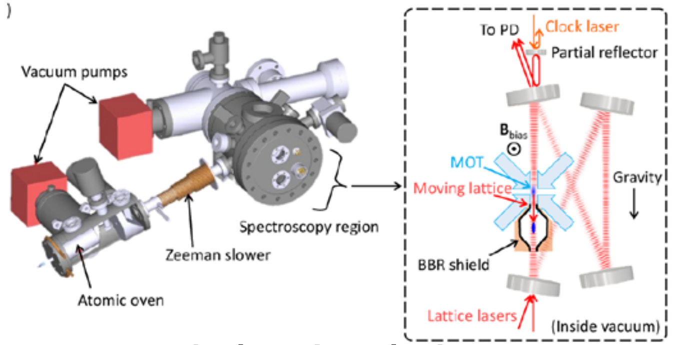
Atoms in optical lattice

Counter



Optical Frequency Comb

- ❑ Have you ever wondered how the clock keeps time?
- ❑ Have you ever thought of building a clock?
- ❑ Have you ever tried tracking how slow your clock becomes after a month or a week?



Optical Lattice Clock setup

If you have thought about these questions or you are interested to find out the answers to these questions, then this project might be suitable for you. Following is a brief description of the basic building blocks of a clock and the project where we want you to join us in building an experimental setup that will realize one of the most accurate and precise clocks in the world.

- ❑ A clock needs an oscillator, a reference, and a counter to work. A particular number of oscillations of the oscillator defines one second. However, the reference needs to give feedback to the oscillator not to correct for inaccuracy. Finally, we need a counter to measure the number of oscillations to know what is the time.

- ❑ In this project, you will construct an experimental setup that will be used to measure time with an accuracy of 1 part in 10^{18} via trapping Strontium atoms in an optical lattice and manipulating them. This clock can serve as a better time reference for the country. The project involves understanding and designing such a system. Assembling the components and achieving ultra-high vacuum. Finally, test the performance of the system.

Skills at play: Vacuum technology, optics, electronics.

[1] M. Takamoto et al., [Nat. photonics. 14, 411-415 (2020).]

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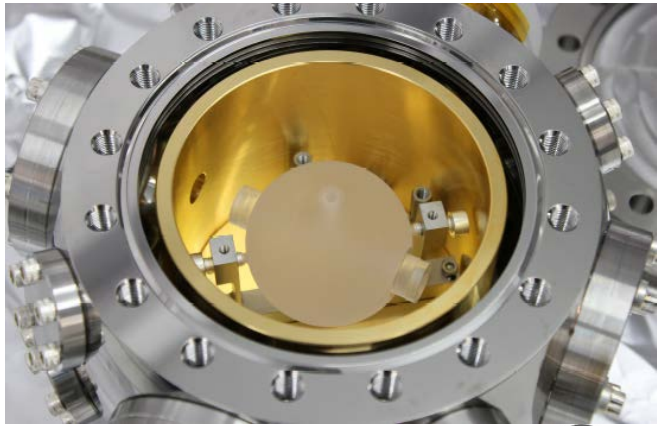
Ultra-narrow linewidth optical clock laser

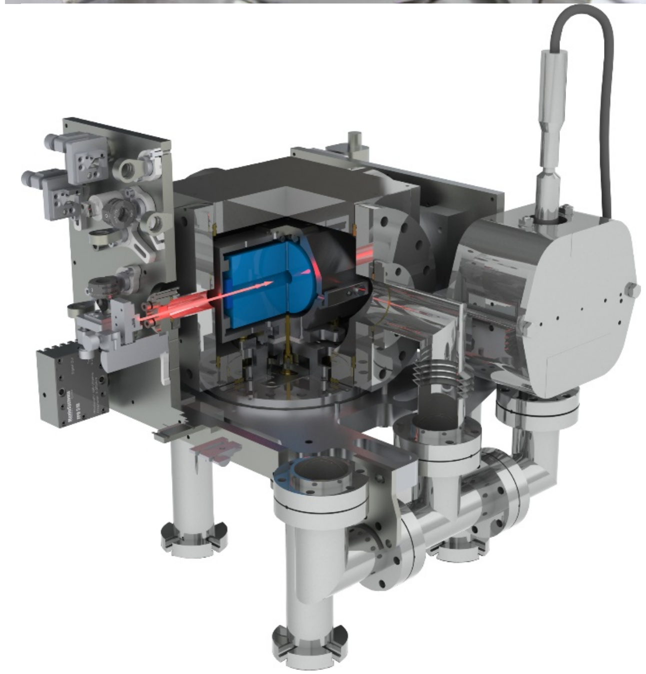


This project will deal with the realization of a reference laser that will feed into our laboratory infrastructure and allow high precision measurements and frequency comparisons with other universities. High-precision many body experiments, atomic clocks, and quantum simulators all rely on high-accuracy reference lasers in order to perform demanding interrogation of their internal degrees of freedom. You will construct an ultra-stable reference laser that will act as a central tool to many of these experiments. The system uses a low-noise laser stabilized to an optical reference cavity that relies on length fluctuations smaller than the size of a proton.

For centuries time keeping has been one of the drivers of physics and today it remains one of the best ways to test our understanding of nature. Time is the physical quantity we are now able to measure most precisely at 1 part in 10^{18} so it is natural that optical clocks [1] are now being used to study the very foundations of physics such as the search for variations in the fundamental constants or searches for dark matter.

In the strontium quantum gas lab, we are developing new types of optical atomic clocks, atom interferometers and quantum simulators that all require high-precision lasers to address ultra-narrow qubit transitions.

This project will focus on the construction of a laser used as a reference for all our experiments. To lock a laser and reduce its linewidth well below 1 Hz requires an exquisite control over all noise sources. You will setup the laser source, will couple it to an ultra-stable high-finesse optical cavity, and will characterize both the laser linewidth, stability, and noise compensation from the lock.



Skills at play: laser physics, optics, cavity physics, high-end analog electronics.

Contacts

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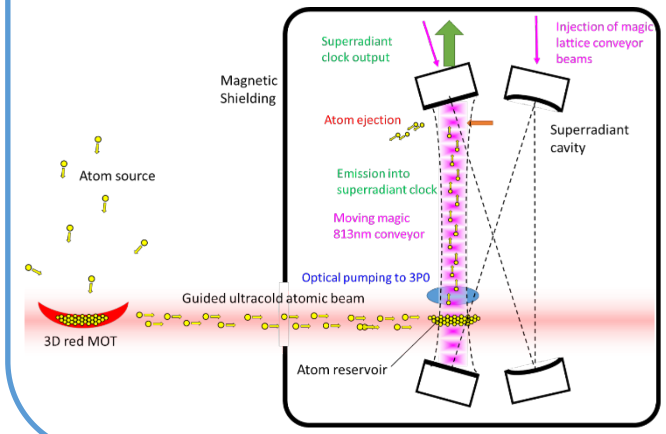
[1] T. L. Nicholson et al., Nat. Commun. 6, 6896 (2015).

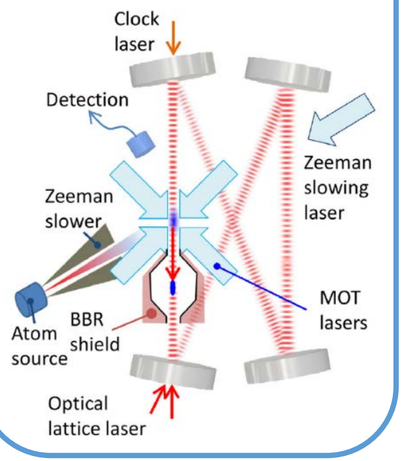
Magic lattices for better quantum clocks

Time is the physical quantity we are now able to measure most precisely at 1 part in 10^{18}. Thus, optical clocks [1] are now being used to study the very foundations of physics such as the search for variations in the fundamental constants or searches for dark matter. In the strontium quantum gas lab, we are developing new types of optical atomic clocks aiming to improve both accuracy and precision crucial for applications from quantum computing to quantum sensing.

mHz continuous superradiant clock [2]



Optical Lattice Clock [1,4]



This project will involve building the magic lattice laser system and locking systems for use in two optical atomic clocks. A magic lattice is special because it allows optical trapping of atoms without causing a light shift to the clock transition. First, this will be used to create the optical conveyor transporting atoms within the mHz continuous superradiant clock now under construction. Superradiant optical clocks promise up to 10^6 reduction in short term noise compared to conventional approaches [2]. Secondly, an ultra-high vacuum ring cavity will be developed for a new optical lattice clock, the Dutch national optical clock. By using this magic lattice to trap and transport atoms into a cryogenically cooled shield it should be possible to control blackbody radiation shifts, the biggest shifts in strontium optical lattice clocks allowing new accuracy records for optical clocks.

Skills at play: laser physics, optics, cavity physics, electronics.

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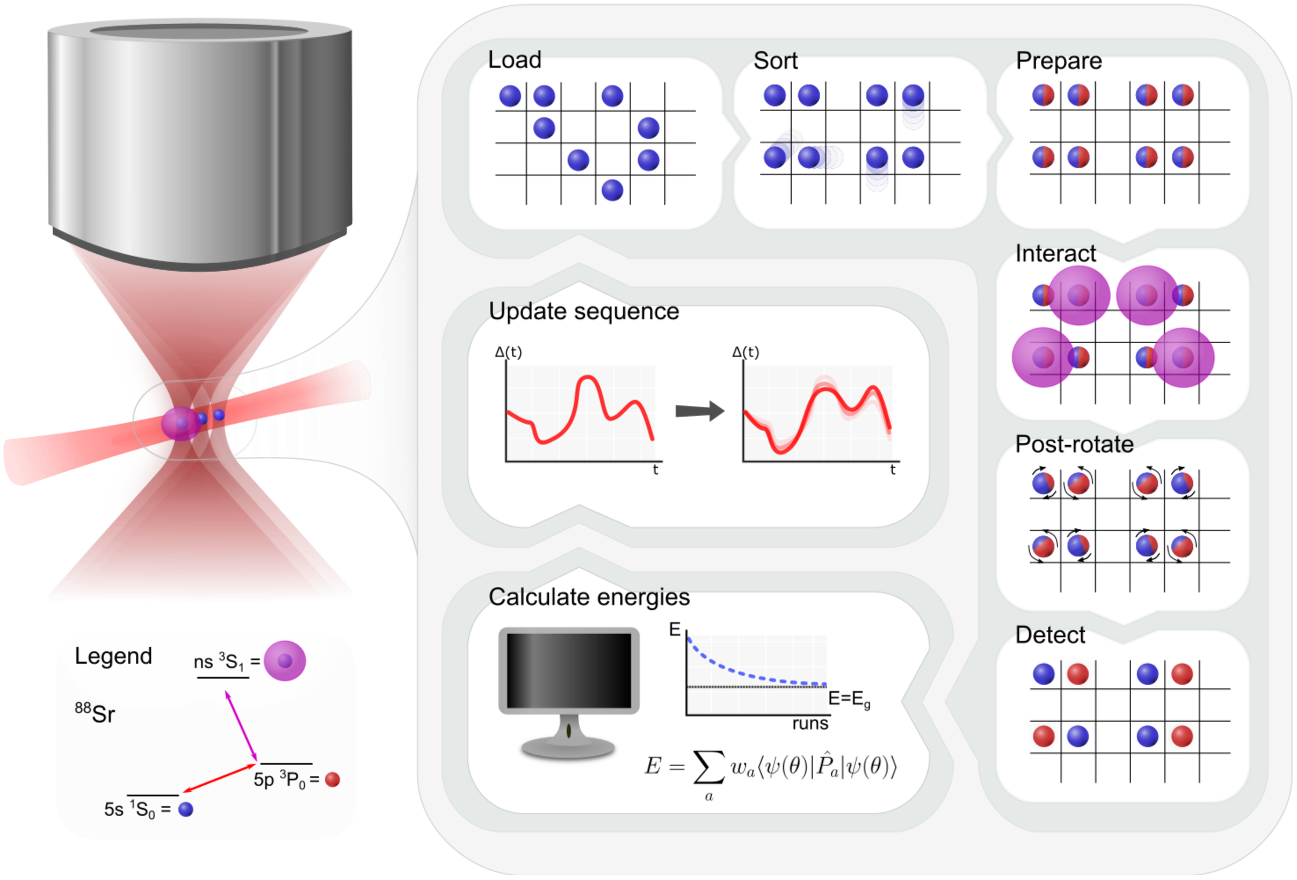
[1] T. L. Nicholson et al., Nat. Commun. 6, 6896 (2015).
[2] D. Meiser et al., Phys. Rev. Lett. 102, 163601 (2009)
[3] M. Takamoto et al., Appl. Phys. Lett. 120, 140502 (2022)

Building single- and multi-qubit gates with Sr



This project is about realizing single- and multi-qubits gates on the Sr tweezer machine. These operations are essential requirements for a programmable quantum computer.

What you will be doing

In the project, you will assist the team in realizing these gates by building, aligning, and characterizing subsystems (e.g. laser systems or electronics), performing supporting calculations, and various other experimental tasks, depending on the need of the team and on your own interests.

Using neutral atoms for a quantum computer

On the left we show a schematic of the type of (hybrid) quantum computer that we are building in our team, a Variational Quantum Eigensolver. The colored balls depict single Sr atoms that are held in tightly focused laser beams. These will become our qubits. After loading the atoms in an array, we can sort the atoms and prepare an initial superposition state of two internal states of the atoms (red/blue). This state-control of a single qubit is called a *single-qubit gate*. By creating a coupling between the excited state and an highly excited Rydberg state (purple), we can let different qubits interact with each other. This forms the *multi-qubit gates*. After all gate operations required for the scheme we want to calculate, we detect the outcome in terms of final states of the atoms. We then process the results classically to get an energy measure and adjust parameters (e.g. laser frequencies, pulse durations) to minimize the energies, solving for the ground state of the system.

Skills at play

laser physics, optics, electronics, programming

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