Bachelorarbeiten AG Lechner

"Two-body CNOT-gate with Alkali-earth Rydberg atoms".
General motivation
Quantum error correction (QEC) stands at the forefront of modern quantum computing science. Among the promising approaches to QEC is the use of quantum repetition codes (QRC) [1,2], which provide a mechanism for error mitigation and robust quantum computation.
A fundamental component of QRC is the controlled-NOT (CNOT) gate—a two-qubit logical gate that flips the "target" qubit from logic 1 to 0 or vice versa, depending on the state of the "control" qubit. Developing an efficient and reliable CNOT gate for quantum systems is the central objective of this Bachelor project.
Project Specification
Rydberg atoms, characterized by a single electron in a highly excited state, exhibit long lifetimes and strong interactions due to their large dipole moments. These features make them ideal candidates for hardware in quantum computation. Recently, a concept for a CNOT gate using Rydberg atoms of rubidium (Rb) was proposed [3]. While Rb atoms have been extensively studied in Rydberg physics, they encounter a critical limitation: their inability to remain trapped during their Rydberg state.
To address this limitation, alkali-earth metal atoms such as strontium (Sr) offer a promising alternative. This project aims to reproduce the results of the Rb-based CNOT gate from Ref. [3] and adapt them for the specific parameters of Sr atoms. By leveraging the advantages of Sr atoms, the project seeks to advance the development of a more practical and efficient CNOT gate for quantum error correction applications.

Student Expectations
The student undertaking this project should:
1) Familiarize themselves with the foundational principles of quantum error correction and Rydberg atom interactions.
2) Reproduce the theoretical and computational results of the Rb-based CNOT gate as outlined in Ref. [3].
3*) Adapt and refine the model for Sr atoms, accounting for their unique properties and interactions.

[1] Nielsen, M.A. and Chuang, I.L. (2011) Quantum Computation and Quantum Information: 10th Anniversary Edition. 10th Edition, Cambridge University Press, New York.
[2] Wootton, J. R., & Loss, D. (2018). Repetition code of 15 qubits. Physical Review A, 97(5), 052313.
[3] Li, R., Li, S., Yu, D., Qian, J., & Zhang, W. (2022). Optimal model for fewer-qubit CNOT gates with Rydberg atoms. Physical Review Applied, 17(2), 024014.

Quantum Walks
Quantum walks (QW) [1, 2] are a form of quantum computing which may be used to solve optimization problems. If we see the possible states of an optimization problem as the vertices of a graph, each with an energy set by the problem Hamiltonian H_p, then the hopping Hamiltonian H_h, defines how a quantum walk may travel from vertex to vertex. If we evolve H_QW=g*H_h +H_p, where g is the hopping rate, after a time t_f, we find the ground state. This corresponds to the answer to the optimization problem.

Typically a Hypercube hopping Hamiltonian (which flips single qubits at a time) is used for quantum walks in the optimization setting, however alternative hopping Hamiltonians with more complex structures may also be used. The aim of this project is to investigate the performance of quantum walks using alternative hopping Hamiltonian graph structures.

[1] Viv Kendon, 2020, RSFS, 0143
[2] Adam Callison et al 2019 New J. Phys. 21 123022

QAOA and its variants

This thesis aims to compare QAOA [1] with one of its variants, namely multi-angle-QAOA (ma-QAOA) [2]. QAOA is short for Quantum Approximate Optimization Algorithm. It is a quantum-classical algorithm for digital quantum computers and aims to find approximation solutions to combinatorial optimization problems. Since its introduction several adaptions have been proposed, with ma-QAOA being one of them.

The goal is to compare how the performance of these two algorithms behaves, depending on different resources (for example the number of classical parameters or the depth of the circuit).

[1] Farhi, E, et al, A Quantum Approximate Optimization Algorithm arxiv:1411.4028v1 (2014)

[2] Herrman, R., *et al.* Multi-angle quantum approximate optimization algorithm. *Sci Rep* **12**, 6781 (2022).