

EBERHARD KARLS UNIVERSITÄT TÜBINGEN  
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MASTER THESIS

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**Master thesis**

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*in*

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## Declaration of Authorship

I, Leopold BODAMER, declare that this thesis titled, “Master thesis” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while applying for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

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Date:

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## Chapter 1

# Introduction

### 1.1 Coherence and Excitation Transport

In this chapter, we aim to explain the phenomena of long coherences (lifetimes) and the excitation transport of light on a microtubule. The proposed model takes the following approach:

- The microtubule is modeled as a cylindrical structure consisting of nodes. Each node represents an atom, which is modeled as a two-level system. The number of atoms,  $N_{\text{atoms}}$ , is determined by the number of chains ( $n_{\text{chains}}$ ) and the number of rings ( $n_{\text{rings}}$ ), assuming fixed positions for these nodes.
- The system is restricted to a single excitation.
- A time-dependent coupling to an electric field is proposed, which may be either classical or quantum in nature. This coupling is intended to facilitate spectroscopy.
- Two types of Lindblad operators are introduced to model dissipation processes. Specifically:
  1. Spontaneous decay
  2. Dephasing

The Lindblad operators introduced to model the spontaneous decay and dephasing processes for each individual atom are defined as follows:

$$C_{\text{decay}}^{(i)} = \sqrt{\gamma_0} \sigma_-^{(i)}, \quad (1.1)$$

$$C_{\text{dephase}}^{(i)} = \sqrt{\gamma_\phi} \sigma_z^{(i)}, \quad (1.2)$$

where:

- $C_{\text{decay}}^{(i)}$  describes the spontaneous decay of the  $i$ -th atom, with a rate given by  $\gamma_0$ .
- $C_{\text{dephase}}^{(i)}$  describes the dephasing of the  $i$ -th atom, with a rate given by  $\gamma_\phi$ .
- $\sigma_-^{(i)}$  is the lowering operator for the  $i$ -th atom, and  $\sigma_z^{(i)}$  is the Pauli  $z$ -operator for the  $i$ -th atom.

## 1.2 Motivation

Quantum computing, an exceptionally promising area of study in modern physics, offers a fundamentally new way to process and transmit information. Applications of this, not yet scalable technology range from cryptography to drug research. Quantum computers would especially outperform classical computers in quantum simulations of chemical / physical systems [Eddins2022]. Qubits, the analog to classical bits, for example, photons or atoms play a crucial role in harnessing this quantum technology [Ramakrishnan2023]. The area which describes photons and their interaction with matter is quantum optics. One essential goal of this field is to build efficient and controllable interactions between photons and atoms. A challenge for this is unwanted (spontaneous) emission, where photons are scattered into channels out of control. This spontaneous emission hampers the development of quantum technologies, especially in quantum information processing. Subradiant states are a promising concept for this field of study. These states appear when many emitters interact via light-mediated resonant dipole-dipole interactions and inherit lifetimes magnitudes larger than that of a single emitter [AsenjoGarcia2017]. Insights into information transport within complex systems are of utmost interest, as they could lead to advances in quantum computing. Especially with subradiant states, as they also offer ultrafast readout [Scully2015].

The goal of this thesis is to perform robust directional photon routing on atomic systems in free-space using subradiant states. Focusing on a Y-shaped atomic tree, different topologies are explored to enable long-lived information transport as a proof of concept.

## 1.3 Outline

This thesis is structured as follows. Chapter ?? introduces the theoretical background. It covers the concepts of open quantum systems, subradiance and superradiance, the Green tensor, and the reciprocal space. These tools are essential foundations for describing atom-atom interactions in free space, including dipole-dipole interactions and coupling to a photonic bath. The quantum router of [Startingpoint] is presented and summarized in Chapter ?. It introduces the concepts of graph theory and explains how quantum evolution on a graph topology can be utilized to achieve directional routing of information. Chapter ? will be the core of this thesis, adapting this model to an atomic system. This chapter delves into the challenges of implementing directional routing in a fully connected atomic system and investigates various solutions to control the phase of interactions. It further extends the analysis to systems with a larger number of atoms, focusing on coupling control and routing capabilities in different configurations, such as equilateral and isosceles triangles. Chapter ? concludes the thesis by summarizing the results and discussing potential future directions in the field of quantum routing in atomic systems.