Thesis Information

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Thesis Title: Open Quantum Systems in the Strongly Interacting Regime

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PhD Program at the University of Yaounde 1

Summary of the Thesis Project

Open quantum systems are systems that interact with their environment, providing a fascinating opportunity to explore phenomena such as **decoherence**, **relaxation**, and **dissipative dynamics.** In particular, the **strong interaction regime** remains largely unexplored. In this context, the effects of interactions between particles dominate those of the environment, leading to captivating emergent behaviors, such as the formation of **quantum phases** or **long-range correlations.**

This thesis project aims to study these open quantum systems in this regime by developing theoretical models and advanced numerical simulations. Among the approaches considered are the use of **Hierarchical Equations of Motion**, **tensor networks**, and **quantum Monte Carlo methods.** The goal is to identify new dynamic behaviors and propose experimental signatures that could be applied to physical systems, such as **superconducting circuits.**

The results of this work could have a significant impact on our understanding of quantum dynamics and pave the way for applications in emerging quantum technologies, including **quantum simulators**, **high-precision sensors**, and **quantum thermodynamics.**

Scientific Project

1. *Context and Position of the Project on the International Scale*

Scientific Context

Research on open quantum systems has made significant strides in recent years, particularly in studying phenomena like decoherence and dissipative dynamics. However, the regime of strong interactions remains a largely unexplored area. The intense interactions between particles in these systems can lead to fascinating emergent behaviors, such as the formation of quantum phases and long-range correlations. This project aims to bridge this gap by developing theoretical models and advanced numerical simulations to explore these complex dynamics.

International Positioning

On the international stage, several research groups, notably at Xiamen University, led by Professor ***Dral Pavlo*** and his collaborators, focus on the study of dissipative dynamics in quantum systems with weak interactions. ***Dr. Arrif Ullah*** investigates this non-recursive dynamics using a convolutional neural network model, but few specifically examine the regime of strong interactions. Our approach, which incorporates tools like ***Hierarchical equations of motion*** and ***tensor networks***, stands out due to its ability to effectively model the interaction effects in these systems.

Potential collaborations could develop with researchers from these institutions, facilitating knowledge exchange and methodological advancements. This could also open doors for joint projects, further strengthening our position in the field.

Potential Impact

The outcomes of this project could significantly enhance our understanding of quantum dynamics and their applications in emerging technologies, such as quantum simulators and high-precision sensors. By identifying new dynamic behaviors, we could propose actionable experimental signatures, thereby contributing to advancements in quantum materials and quantum thermodynamics.

2. Scientific Targets

As part of our project, we have defined several key scientific objectives that will guide our research on open quantum systems in the strongly interacting regime. One of our main goals is to develop innovative theoretical models that accurately describe the dynamics of open quantum systems when particle interactions are intense. This includes incorporating non-Markovian effects, which are often overlooked in traditional approaches.

Additionally, we will utilize advanced methods, such as tensor networks and quantum Monte Carlo simulations, to model the behavior of these systems under various interaction conditions. This approach will allow us to observe phenomena that analytical models may not always predict.

Next, we will focus on identifying and studying emergent behaviors, such as the formation of quantum phases and long-range correlations. This could open new perspectives on understanding complex quantum interactions. We will also seek to understand how strong interactions affect decoherence and relaxation dynamics within these systems. Developing quantitative metrics to evaluate these effects is crucial for preserving quantum states.

Based on our theoretical and numerical results, we will propose concrete experimental setups to validate our hypotheses. This includes collaborations with experimental laboratories to test our ideas. Finally, we will explore the implications of our findings for emerging quantum technologies. By identifying relevant dynamic behaviors, we hope to contribute to advancements in quantum simulators and high-precision detection devices.

3. Originality and Innovative Aspects of the Project

Although open quantum systems have been extensively studied in weakly interacting regimes, their behavior under strong interactions remains largely uncharted. This research aims to fill this gap by exploring the interplay between dissipation, decoherence, and strong correlations, which can lead to new emergent phenomena that are absent in weakly interacting systems. Moreover, the project seeks to push the boundaries of existing models by combining advanced theoretical approaches with high-performance numerical techniques. By collaborating with experimental groups or referencing realizable physical systems—such as ultracold atoms in optical lattices, cavity QED systems, or superconducting circuits—the project aims to propose experimentally testable predictions. This emphasis on practical validation ensures that the research has direct applicability to cutting-edge quantum technologies.

This work lies at the intersection of quantum physics, condensed matter, and quantum information. Its findings could contribute to various fields, including quantum simulation, quantum thermodynamics, and error correction protocols, ultimately aiding in the development of quantum computing and sensing technologies. By venturing into unexplored territory, this research has the potential to reveal innovative collective behaviors and emergent quantum phases in open systems. These discoveries could pave the way for new theoretical paradigms and experimental breakthroughs.

4. Description of the Thesis Objectives and Proposed Research Program

- Strategy, methods, and techniques
- Contribution to the expected project achievements
- Describe how the research program will contribute to quantum technologies

Thesis Objectives

The main goal of this thesis is to explore and understand the dynamics of open quantum systems in the regime of strong interactions, where the interplay between dissipation, decoherence, and strong correlations gives rise to novel emergent phenomena. Specifically, the proposed research objectives are as follows:

1. **Develop Theoretical Models for Strongly Interacting Open Quantum Systems**:
2. **Investigate Dissipative Dynamics and Steady-State Properties**:
3. **Identify Experimentally Testable Phenomena**:
4. **Explore Applications in Emerging Quantum Technologies**:

Proposed Research Program

To achieve these objectives, the research program will be divided into three main phases, corresponding to the progression of theoretical development, numerical implementation, and experimental relevance:

Phase 1: Theoretical Foundations

a) Conduct a comprehensive review of existing literature on open quantum systems, focusing on both weakly and strongly interacting regimes.
b) Incorporate strong interactions and non-Markovian effects into the formalism of open quantum systems using advanced techniques such as tensor network representations.

Phase 2: Numerical Simulations

a) Implement numerical methods to simulate the dynamics of strongly interacting open systems
b) Validate theoretical predictions for specific physical systems, such as Bose-Hubbard models in dissipative environments or spin systems coupled to structured reservoirs.

Phase 3: Experimental Relevance and Applications

a) Collaborate with experimental groups or utilize available experimental data to test theoretical predictions.
b) Propose experimental setups or protocols to verify the predicted phenomena.

Expected Contributions

The proposed research program aims to contribute to the following areas:

- **Fundamental Physics**: Generate deeper insights into the complex interplay of dissipation and strong correlations in quantum systems.

- **Experimental Quantum Science**: Provide a theoretical roadmap for studying strongly interacting open systems in current or near-future experimental platforms.
- **Quantum Technology Development**: Suggest innovative ways to utilize dissipation and interactions as resources for robust quantum devices.

5. Expected Outputs and Timeline

Expected Outcomes

The research on open quantum systems in the regime of strong interactions is expected to yield significant results and contributions. This includes the development of new theoretical frameworks to describe the dynamics of these systems, the implementation of advanced numerical techniques to simulate strongly interacting open systems, and the identification of key experimental signatures that can validate theoretical predictions. These signatures may involve spectral properties, relaxation dynamics, or quantum correlations in systems such as ultracold atoms, superconducting circuits, or cavity QED setups.

Proposed Timeline

The proposed research program will be conducted over a period of three years, divided into distinct phases:

Year 1: Foundational Work

- Conduct an extensive review of the literature on open quantum systems and strongly interacting systems, along with basic numerical simulations to validate theoretical approaches.

Year 2: Advanced Theoretical and Numerical Studies

- Extend the theoretical models to more complex systems, incorporating strong correlations and non-Markovian effects. Study specific physical systems of interest, such as dissipative Bose- Hubbard models or spin systems coupled to structured reservoirs.

Year 3: Experimental Relevance and Optimization

- Focus on identifying experimentally testable signatures and refining predictions for physical platforms like ultracold atoms, superconducting circuits, or cavity QED systems.
- Propose protocols or setups for experimental validation in collaboration with experimental groups.
- Explore potential applications of dissipation and strong correlations in quantum sensing, quantum simulation, or error correction.
- Publish findings in peer-reviewed journals and present results at international conferences.

6. Driving Forces and Outcomes of the Project

Project Motivations

With the rise of quantum technologies, there is an increasing need to understand non-equilibrium dynamics in open systems, which are inherently coupled to their environments. These dynamics govern processes such as relaxation, decoherence, and the formation of steady states, all of which are crucial for real-world quantum devices. Advances in experimental techniques (such as ultracold atoms, superconducting circuits, and cavity QED) have made it possible to simulate complex quantum systems, including those with strong interactions. However, the theoretical frameworks needed to describe and predict their behavior under dissipation are still underdeveloped. This project aims to fill that gap and contribute to the synergy between theory and experiment.

7. Assets and Suitability of the Candidate for the Project

I am the ideal candidate for this project, as I possess a unique combination of skills and experiences that align perfectly with its objectives. My expertise in quantum optics, reinforced by my master's research, has focused on predicting excitation energy transfer in the photosynthetic light-harvesting complex to optimize the efficiency of organic photovoltaic cells. This work has led me to explore open quantum systems in depth, particularly the Fenna-Matthews-Olson complex, allowing me to develop a strong command of the tools and concepts essential for this project.

I am also highly motivated, as quantum optics and the study of open quantum systems are fields I am deeply passionate about. I firmly believe that this project can make a significant contribution to the understanding of this rapidly evolving domain. Moreover, after researching the team and the institution, I was particularly impressed by the available resources and the expertise of the researchers involved.

8. Interdisciplinary Aspects

Our project is inherently interdisciplinary, as it combines quantum optics and many-body physics. The study of open quantum systems in the strongly interacting regime requires a deep understanding of quantum coherence and many-body correlations. It also relies on open quantum systems theory and advanced computational and theoretical methods, incorporating frameworks such as QuTiP, HierarchicalEOM, and tensor networks.

9. Ethics

Our research project on open quantum systems raises several important ethical considerations. As a researcher, I am committed to taking my responsibilities seriously. First, I am aware of the potential environmental impact of my experiments and will take concrete steps to minimize the energy resources used. Furthermore, I am fully aware of the sensitivity of the data generated by my simulations and experiments. I will take robust measures to protect this data and ensure its confidentiality. Finally, I am aware of the potential implications of my research for security and defense. I will take measures to ensure that my research is not used for malicious purposes. I am also convinced that collaboration and knowledge sharing are essential for advancing research in this field.

10. References

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