Internship and PhD thesis proposal (D. Lacroix, IJCLab)

Title: **Non-equilibrium dynamics in strongly entangled systems described with quantum computers**

Abstract

Non-equilibrium dynamics in strongly entangled systems pose major computational challenges, as classical methods struggle to handle large particle numbers and high entanglement. This PhD project aims to harness recent advances in quantum computing to simulate such systems. At IJCLab/Paris Saclay University, prior work has focused on static properties of interacting particles, but this research will extend to time-dependent, non-equilibrium phenomena, which are more computationally demanding.

The project's goals are threefold: (1) to deepen the understanding of quantum information theory, particularly in quantifying entanglement, (2) to master quantum simulation techniques for systems of interacting particles, and (3) to apply and potentially enhance existing quantum algorithms for simulating non-equilibrium dynamics. These simulations will be performed using IBM's Qiskit quantum computing platform, with a focus on systems where interaction strength can be controlled.

This research holds potential for significant breakthroughs in fields like nuclear physics, neutrino oscillations, and condensed matter, where strongly entangled particles and non-equilibrium dynamics are critical. By expanding the capabilities of quantum simulations, the project could contribute to both the development of new quantum algorithms and a deeper understanding of fundamental physics.

Summary

Quantum computing has seen substantial advancements in recent years, driven by technological progress and the emergence of functional quantum platforms [1]. At IJCLab/Paris Saclay University, the nuclear physics team has been actively working on this topic over the past few years, with efforts directed toward pioneering applications in both nuclear and neutrino physics [2-4]. Additionally, new approaches in quantum computing and quantum information have been explored. Recent research has primarily focused on modeling the static properties of strongly interacting systems, leading to the development of novel quantum algorithms. Looking ahead, we aim to extend this work to address non-equilibrium problems, which present greater computational challenges.

When dealing with physical systems composed of interacting particles, classical computers struggle to handle large particle numbers or high levels of entanglement. While weakly entangled systems can be efficiently simulated on classical computers using tensor product state methods, these techniques break down as entanglement grows. In general, quantum computers are expected to offer advantages over classical systems, particularly when dealing with strongly entangled particles.

The proposed internship will focus on the following objectives:
1. **Understanding and applying foundational methods in quantum information theory,** with an emphasis on quantifying entanglement in physical systems.
2. **Acquiring the skills needed to perform cutting-edge quantum computer simulations** of interacting particles.
3. **Applying these techniques to simulate simplified systems of interacting particles** where the interaction strength can be varied. These simulations will be performed using a quantum computer emulator, specifically the IBM Qiskit software. Existing quantum algorithms will be employed for time-dependent simulations, and if necessary, new methods will be developed and implemented.

This internship could potentially lead to a PhD thesis continuation, aimed at deepening the understanding and simulation of strongly entangled systems. Potential applications may include non-equilibrium simulations relevant to neutrino oscillations, nuclear physics, and condensed matter systems.

[1] T. Ayral, P. Besserve, D. Lacroix and A. Ruiz Guzman, Quantum computing with and for many-body physics, Eur. Phys. J. A 59 (2023).
[2] D. Lacroix, E. A. Ruiz Guzman, and P. Siwach, Symmetry breaking/symmetry preserving circuits and symmetry restoration on quantum computers Eur. Phys. J. A 59 (2023) 3.
[3] Alberto Di Meglio et al. Quantum Computing for High-Energy Physics: State of the Art and Challenges, PRX Quantum 5, 037001 (2024)
[4] D. Lacroix, A. B. Balantekin, Michael J. Cervia, Amol V. Patwardhan, Pooja Siwach, Role of non-gaussian quantum fluctuations in neutrino entanglement, Phys. Rev. D 106, 123006 (2022); Denis Lacroix, Angel Bauge, Bulent Yilmaz, Mariane Mangin-Brinet, Alessandro Roggero, A. Baha Balantekin, Phase-Space methods for neutrino oscillations: extension to multi-beams, arXiv:2409.2021

Requirements:

We are seeking a highly motivated candidate with a background in one or more of the following areas:
- Many-body physics
- Numerical methods for physics problems
- Quantum Information
- Basic knowledge of quantum computing

Responsibilities:

The successful candidate will be responsible for:
1. Developing quantum algorithms for simulating many-body systems presenting strong entanglement such as those in nuclear, neutrino, or condensed matter physics.
2. Conducting comparative studies between quantum and classical computing approaches to assess the advantages of quantum computing.
3. Analyzing the emergence of entanglement and decoherence in these systems.

Application Process:

Interested candidates should submit the following documents to Denis Lacroix (lacroix@ijclab.in2p3.fr, IJCLab, Orsay, France).
1. Curriculum Vitae (CV)
2. Cover letter detailing your qualifications, research interests, and motivation for pursuing this project.
3. Academic transcripts and certificates.
4. One recommendation letter.

Financing for the PhD is possible through the standard Ecole Doctorale PHEENICS process or with specific grants like ENS grants.