Integrability in the design and control of quantum devices*

Tese de Doutorado - Press Release

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Quantum mechanics is a probabilistic theory that very accurately simulates the behavior of microscopic, atomic, and subatomic physical systems. It arises gradually, to account for experimental results not explained by Newtonian physics. One of the first important insights was the recognition that every quantum entity presents a dual wave-particle behavior, which reveals the probabilistic behavior of quantum systems. The wave-particle duality and the Uncertainty Principle are the soul of the Theory of Quantum Mechanics, and underlie quantum phenomena such as tunneling, superposition of states, and entanglement. These phenomena are still weird to us, but they have great potential to drive information technologies, mainly because quantum information can coexist, in an entangled way, in different locations, while they can also coexist in the same place, in a superposition of states, as in Schrödinger's thought experiment (1935), where a theoretical cat can be simultaneously in both "dead" and "alive" states.

Quantum phenomena, in general, are not easily observed. But there is a state of matter, predicted by Einstein in 1925, where these phenomena reveal themselves to the real world. One architecture for implementing this state is through ultracold atomic systems, where atoms are trapped and cooled to temperatures close to absolute zero. In this environment, the wave behavior of an atom is pronounced and the superposition of these waves forms a new state of matter known as a Bose-Einstein condensate (BEC). The BEC was obtained experimentally in 1995, stirring up the scientific milieu and boosting the area of ultracold atoms. Systems of ultracold atoms have been used as instruments of conceptual research and as an alternative to new quantum technologies, giving rise to the area of Atomotronics!

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In this thesis, we present designs of quantum devices that can, in principle, be implemented through ultracold atom technologies. To describe these systems, we use integrable mathematical models. Integrability in mathematics refers to equations with special characteristics that allow a deep understanding of their properties. In our work, we find new applications of integrability to gain an understanding of how to prepare physical quantum states and devices. First, we show how to accurately produce and control a switching device, analogous to a transistor, for ultracold atoms trapped in a three potential well optical system. We show that this system also has an intrinsic ability to generate entangled states. Stimulated by these findings, we study an integrable model of four potential wells, in the search for a certain class of entangled quantum states, known as NOON states, which are analogous to the "cat-states". Using this structure, we design protocols to generate systems of both interferometry and NOON states, with accurate phase encoding, with potential applications in quantum metrology, sensing and information.

Our work exposes an important and inspiring role of integrability in the development of new technologies in quantum physics. We believe that the proposed models have great appeal in the implementation of ultracold atom technologies, possibly acting as building blocks in the emerging quantum technologies!