



INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
PhD-17 SHORT ABSTRACT OF THESIS

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Thesis Title: **Quantum Vortex Lattices and Collective Modes of Rotating Bose- Einstein Condensates with Synthetic Gauge potentials**

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SHORT ABSTRACT

The realization of Bose–Einstein condensation in dilute atomic gases has provided an exceptional platform for exploring fundamental aspects of quantum many-body physics in a highly controllable environment. One of the most remarkable manifestations of superfluidity in these systems is the formation of quantized vortices when the condensate is subjected to rotation. At sufficiently high rotation frequencies, these vortices organize themselves into ordered lattice structures, typically forming the well-known Abrikosov lattice. The study of vortex lattices in Bose–Einstein condensates (BECs) has therefore become an important avenue for understanding the interplay between rotation, interactions, and external potentials in quantum fluids. Recent experimental and theoretical developments have significantly expanded the scope of research in this field. Techniques such as optical lattices, disorder potentials, and synthetic gauge fields have enabled unprecedented control over ultracold atomic systems. Optical lattice potentials can pin vortices and induce structural transformations of vortex lattices, while disorder in the form of impurities can destabilize ordered configurations and lead to vortex-lattice melting and turbulent dynamics. In parallel, the engineering of synthetic gauge potentials has opened new possibilities for simulating electromagnetic effects in neutral atomic gases, leading to novel rotational phenomena and modified condensate dynamics. These developments provide a rich framework for investigating vortex structures, their stability, and their collective excitation spectra. Another important aspect of rotating condensates is the study of their collective excitations, which provide valuable insights into the dynamical stability and physical properties of the system. The Bogoliubov–de Gennes (BdG) formalism serves as a powerful theoretical tool for analyzing these excitations. In particular, the presence of density-dependent synthetic gauge potentials can introduce nonlinear rotational effects, significantly altering both the equilibrium structure of the condensate and the corresponding excitation spectrum. Motivated by these developments, this thesis investigates the structural transformations and collective excitation dynamics

of vortex lattices in rotating Bose–Einstein condensates under the influence of optical lattice potentials, impurities, differential rotation, and density-dependent synthetic gauge potentials. The primary objective is to understand how these external perturbations modify vortex-lattice configurations, induce lattice melting and turbulence, and influence the excitation spectrum of the condensate. The first part of this work focuses on the structural transformation of vortex lattices in the presence of a square optical lattice potential and differential rotation, where the lattice and the condensate rotate at different angular velocities. Using quantitative measures such as the structure factor and lattice energy, we analyze the transition from the conventional Abrikosov lattice to a square vortex lattice through an intermediate coexistence phase. In certain parameter regimes, the ordered lattice structure undergoes melting, leading to irregular vortex motion accompanied by turbulence-like behavior in the kinetic energy spectra. The second part of the thesis examines the influence of impurities on vortex-lattice stability and turbulence in rotating condensates. Both static random impurities and dynamically oscillating obstacles are considered. Our results show that sufficiently strong impurities can destroy the long-range order of the vortex lattice, driving the system into a melted regime characterized by turbulent vortex dynamics. The energy spectra in this regime display characteristic power-law scaling, indicating features consistent with quantum turbulence. The final part of the thesis investigates the effects of density-dependent synthetic gauge potentials on the structure and collective excitation spectrum of rotating condensates. Using the Bogoliubov–de Gennes framework together with analytical and hydrodynamic approaches, we analyze how nonlinear rotation induced by such gauge potentials modifies the excitation modes of the system. The results demonstrate phenomena such as the violation of Kohn’s theorem, significant changes in vortex-displacement modes, and modifications of surface excitation frequencies. In addition, the influence of nonlinear rotation on a toroidally trapped condensate is studied, where a structural transition from a ring-shaped condensate to a giant vortex state is observed. The investigations presented in this thesis are primarily based on numerical simulations of the Gross–Pitaevskii equation using spectral and time-splitting methods, which allow accurate determination of both the ground-state properties and the dynamical behavior of the condensate. Overall, the work presented here contributes to a deeper understanding of vortex-lattice physics and collective excitations in rotating Bose–Einstein condensates, particularly in the presence of structured potentials, disorder, and synthetic gauge fields. The thesis is organized into seven chapters. Chapter 1 introduces the theoretical background and reviews relevant literature. Chapter 2 presents the numerical methods used for solving the Gross–Pitaevskii equation. Chapters 3 and 4 investigate vortex-lattice transformations and turbulence induced by optical lattice potentials and impurities. Chapters 5 and 6 focus on the effects of density-dependent gauge potentials on vortex-lattice structures and collective excitations in ring and Toroidal geometry, respectively. Finally, Chapter 7 summarizes the main findings of the thesis and outlines possible directions for future research.