

Complex Density Wave Orders And Quantum Phase Transitions In A Model Of Square-lattice Rydberg Atom Arrays

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Understanding the intricate behaviors of quantum many-body systems has been a central pursuit in condensed matter physics and quantum information science. Among the most promising platforms for exploring these phenomena are Rydberg atom arrays—highly controllable systems where atoms excited to Rydberg states exhibit strong, long-range interactions. When arranged in a square lattice, these systems reveal a rich tapestry of phases, including complex density wave orders and quantum phase transitions. This article delves into the theoretical modeling of such systems, examining how their unique properties enable the emergence of exotic quantum states, and highlighting recent advances that pave the way for future quantum technologies.

Introduction to Rydberg Atom Arrays

Rydberg atoms are atoms excited to very high principal quantum numbers, resulting in exaggerated atomic properties such as large dipole moments and long lifetimes. These features make Rydberg atoms ideal candidates for quantum simulation and quantum information processing.

Why Square-Lattice Geometry Matters

The square lattice configuration offers a simple yet powerful framework for exploring many-body physics. Its symmetry and geometric constraints influence the types of density wave orders that can emerge, as well as the nature of quantum phase transitions between these states.

Fundamentals of Density Wave Orders in Rydberg Systems

Density wave orders refer to spatial arrangements of excitations—such as Rydberg states—forming periodic modulations across the lattice. These patterns are stabilized by the interplay of interactions, external fields, and quantum fluctuations.

Types of Density Wave Orders

- Checkerboard (Neel) Order: Alternating occupied and unoccupied sites resembling a checkerboard pattern.

- Stripe Phases: Linear arrangements of Rydberg excitations forming stripes across the lattice.
- Complex Superlattice Phases: More intricate arrangements with larger unit cells, often involving multiple sublattice patterns.

Key Factors Influencing Density Wave Formation

- Van der Waals Interactions: Long-range forces that favor certain spatial arrangements.
- Laser Detuning and Rabi Frequencies: External control parameters that tune the excitation probabilities.
- Lattice Geometry: The square lattice's symmetry constrains possible density wave patterns.

Modeling Rydberg Atom Arrays on a Square Lattice

Theoretical models capture the essential physics of Rydberg systems, allowing researchers to predict phase diagrams and analyze phase transitions.

The Rydberg Blockade Model

A widely used effective Hamiltonian describing the system is:

$$H = \sum_i \left(\frac{\Omega^2}{2} \sigma_i^x - \Delta n_i \right) + \sum_{\langle ij \rangle} V_{ij} n_i n_j$$