THESIS DEFENSE: Raman Dressed Bose-Einstein Condensates with Tunable Interactions: Topological Gauge Theories and Supersolids

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June 19, 2023
10:00
Auditorium and Online (Teams)

The exquisite control available in atomic ultracold quantum gases experiments makes them an ideal candidate for quantum simulation of diverse topics ranging from high energy physics and analogue quantum gravity to strongly correlated condensed matter systems and exotic states of matter. This thesis describes the use of Raman coupling to engineer novel chiral interactions and a double well dispersion relation in potassium Bose-Einstein condensates and exploits them to realise a topological gauge theory and an exotic state of matter known as a supersolid, respectively.
A common feature of many topics of interest for quantum simulation is the ability to describe

them from the perspective of a gauge theory. Raman coupling has been used to produce artificial gauge fields for more than a decade but usually the gauge fields lack the symmetry constraints necessary to constitute a gauge theory. A well known gauge theory which is used to describe fractional quantum Hall states is the Chern-Simons theory. The Chern-Simons theory is a topological gauge theory so does not have gauge field dynamics in the absence of matter. We have used optical dressing to create chiral interactions in a Bose-Einstein condensate of potassium atoms and encode the dynamics of a one-dimensional reduction of the Chern-Simons theory known as the chiral BF theory into the dynamics of the matter. We have observed chiral solitons and a density-dependent electric field. Our experimental results represent the first successful quantum simulation of a topological gauge theory in the continuum.

Supersolids were predicted theoretically more than fifty years ago and have been realised in Bose-Einstein condensates in recent years. In a second series of experiments, we have taken advantage of the unique interaction properties of potassium to engineer a supersolid in a Raman coupled Bose-Einstein condensate with greater stability and contrast than what can be achieved with other alkali atoms. Using matterwave optics techniques, we have been able to image the characteristic density modulations of a supersolid in a Raman coupled Bose-Einstein condensate for the first time. We explore a previously inaccessible parameter regime and demonstrate that the fringe spacing depends on the optical intensity, in contrast to a shallow optical lattice where the fringe spacing is given by the lattice wavevector.

Our method of engineering chiral interactions broadens the field of quantum simulation of gauge theories to include topological gauge theories in the continuum and is a step towards simulating the Chern-Simons theory in two dimensions. Our application of matterwave optics to the supersolid phase in a Raman coupled Bose-Einstein condensate introduces a new tool for probing low energy Goldstone modes and phase coherence properties.

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