PhD THESIS DEFENSE: Simulating a topological gauge theory in a Raman-dressed Bose-Einstein condensate.

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Ultracold quantum gases constitute a powerful and versatile tool to experimentally explore quantum many-body physics. This thesis presents an original contribution to the quantum simulation of gauge theories with ultracold atoms, which has evolved into a thriving research field during the last years. Gauge theories form the basis of our modern understanding of nature, with applications ranging from high energy to condensed matter physics. A subclass formed by topological gauge theories plays a key role in the effective description of certain strongly correlated materials. An important example is the fractional quantum Hall effect, where the topological Chern-Simons theory can provide an effective single-particle

description for some of the filling factors. A simpler toy model which already provides access to the key properties of topological gauge theories is the one-dimensional chiral BF theory obtained from Chern-Simons theory after dimensional reduction.

This thesis reports on the quantum simulation of the chiral BF theory in an ultracold gas of bosonic potassium atoms, establishing ultracold quantum gases as a resource for the quantum simulation of topological gauge theories. As a first step, we establish the theoretical framework necessary for the quantum simulation of the chiral BF theory. We start by deriving an encoded Hamiltonian for this gauge theory in which the gauge degrees of freedom are eliminated via the local symmetry constraint. The encoding results in a system with only matter particles that have local but unconventional chiral interactions. We continue by showing that these chiral interactions can be realized in a Raman-dressed Bose-Einstein condensate (BEC) with unbalanced interactions by deriving an effective single-component Hamiltonian from a microscopic view in momentum space.

Subsequently, we present the implementation of the different ingredients necessary to realize the chiral BF theory in our experiment. In a first series of experiments, we study the effects of coherent coupling on the effective collisional properties of the system. To this end, we employ radio-frequency to couple two internal states with unequal interaction in a 39K BEC. We measure the effective scattering length of the system as a function of the coupling field parameters. Moreover, we use the coherent coupling as an interaction control tool and quench the effective interactions from repulsive to attractive values. Afterwards, we turn to the implementation of Raman coupling and characterize the modifications in the dispersion of Raman-dressed atoms at the single particle level. Finally, we demonstrate the realization of the chiral BF theory by combining Raman coupling and unbalanced interactions in a BEC of 39K. We probe the chiral interactions arising in the system and observe the formation of chiral bright solitons which dissolve as soon as their propagation direction is inverted. Moreover, we use the local symmetry constraint of the theory to reveal the BF electric field through measurements on the matter field alone, and show that it leads to an asymmetric expansion of the condensate. Our experiments establish chiral interactions as a novel resource for quantum simulation experiments and pave the way towards implementing topological gauge theories in higher dimensions with ultracold atoms.

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