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Engineering exotic superfluids with spin-orbit coupled Bose-Einstein condensates

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Spin-orbit coupled Bose-Einstein condensates, where the internal state of the atoms is linked to their momentum through optical coupling, are a flexible experimental platform to engineer synthetic quantum many-body systems. In my talk, I will present recent work where we have exploited the interplay of spin-orbit coupling and tunable interactions in potassium BECs to realize two unconventional superfluid phases.

In a first series of experiments, we optically couple two internal states of potassium 39 with very unequal scattering lengths using two-photon Raman transitions. This results in a BEC where the interactions are effectively chiral, i.e. depend on the propagation direction of the atoms. We show that under appropriate conditions the Hamiltonian of the system corresponds to the chiral BF theory: a one-dimensional reduction of the celebrated Chern-Simons gauge that effectively describes fractional quantum Hall states [1]. Our chiral BECs allow us to reveal the key properties of the chiral BF theory: the formation of chiral solitons and the emergence of an electric field generated by the system itself [2]. Our results thus expand the scope of quantum simulation to topological gauge theories and open a route to implement analogous theories in higher dimensions.

In a second series of experiments, we address instead the regime of weak Raman coupling, where the dispersion relation of the atoms acquires a characteristic double-well structure. When the intrawell interactions dominate over the interwell ones, both minima are occupied and their populations interfere, leading to a system with a modulated (striped) density profile. The BEC then behaves as a supersolid: a phase that spontaneously breaks both gauge and translation symmetry, and which combines the frictionless flow of a superfluid and the crystalline structure of a solid. We realize this situation in a spin-orbit coupled potassium 41 BEC, where the difference of intraspin and interspin scattering lengths can be selected using Feshbach resonances [3] and results in a stable supersolid stripe phase over a broad range of Raman coupling parameters. Using a matter-wave lensing technique, we magnify the density profile of the cloud and measure in situ the contrast and spacing of the stripes [4]. Our experiments visualize the crystalline nature of the supersolid stripe phase, and provide an excellent starting point to investigate its excitations.

[1] C. S. Chisholm, A. Frölian, E. Neri, R. Ramos, L. Tarruell, and A. Celi, Phys. Rev. Research **4**, 043088 (2022)
[2] A. Frölian*, C. S. Chisholm*, E. Neri, C. R. Cabrera, R. Ramos, A. Celi, and L. Tarruell, Nature **608**, 293–297 (2022)
[3] L. Tanzi, C. R. Cabrera, J. Sanz, P. Cheiney, M. Tomza, and L. Tarruell, Phys. Rev. A **98**, 062712 (2018)
[4] C. S. Chisholm, *R. Ramos*, J. Cabedo, A. Celi, and L. Tarruell, in preparation

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