Time, Momentum, and Energy Resolved Pump-Probe Spectroscopy of the Quantum Hall System: Discovery of a Metastable Nonequilibrium Spin State

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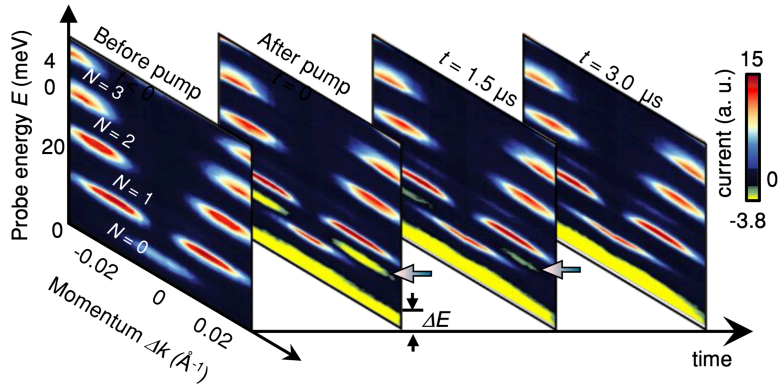

Fig. 1: Energy and momentum resolved spectra of a Quantum Hall System at filling factor 1. At time $t = 0$, electrons are pumped into the N=1 Landau level. Relaxation of these electrons into the N=0 Landau level is monitored through the decay of the yellow dash marked by the arrow.

Spectroscopy of nonequilibrium systems can uncover intricate relaxation mechanisms and exotic many-body interactions that are hidden in strongly correlated materials. Experimenters have extensively used pump-probe methods in ultra-fast optics for studying nonequilibrium phenomena in bulk materials. However, there remains a significant challenge in applying these spectroscopies to two-dimensional (2D) materials at low temperatures, home to a variety of intriguing correlated electronic phases such as superconducting and magnetic states.

We have developed a time, momentum, and energy resolved pump-probe tunneling spectroscopy (Tr-MERTS) that allows high-energy resolution imaging of nonequilibrium states in a 2D electronic system in a strong applied magnetic field and at ultra-low temperatures. Tr-MERTS employs short-duty cycle RF pulses and easily functions in the millikelvin temperature range which has been inaccessible to previous pump-probe spectroscopy. In addition, electrical pulses utilized in Tr-MERTS are easily tunable and permit precise control of pumping electron densities. Finally, since the pumping energy can be tuned by the height of an applied pulse, electrons can be pumped into a specific energy state even for a system with equidistant energy levels.

We visualize the time-dependent change of tunneling spectra in a wide range of filling factors, temperatures, and magnetic fields, all of which can tune the ground-state properties and hence the relaxation dynamics of excited electrons. We observe a substantially slowed-down relaxation process of spin-polarized electrons with lifetimes up to tens of microseconds when the system forms a ferromagnetic ground state. By precisely tuning the pumping electron density, we discover an unexpected splitting in the nonequilibrium energy spectrum in the vicinity of a ferromagnetic state. An exact diagonalization study of the system suggests that the splitting arises from a maximally spin-polarized higher energy state, distinct from a conventional equilibrium skyrmion. We observe time-dependent relaxation of the splitting, which we attribute to single-flipped spins forming topological spin textures.

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