Deconfinement and Dissipation in Quantum Hall "Josephson" Tunneling

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Bilayer quantum Hall systems support interlayer coherent states that bear some important similarities to superconductivity, for example, a sharp tunneling resonance near zero bias that may be a precursor of the Josephson effect. The bilayer system is believed to be described at low energies by the two-dimensional XY model in a transverse magnetic field, the latter arising from tunneling between the layers. Excitations of this model are presumably responsible for the dissipation of the "Josephson current" seen in experiment, but the mechanism by which this happens is unknown and has been a subject of much theoretical effort. In this work, demonstrate using renormalization group (RG) calculations and extensive Langevin dynamics simulations that topological defects – vortices and strings of overturned spins – play a crucial role in dynamics and dissipation in this model.

Because of the transverse magnetic field, a single vortex-antivortex pair is connected by a string, which linearly confines it. Using a Villain model formulation, we map the problem of vortex and string degrees of freedom to one of screw dislocations in a solid-on-solid model. An RG treatment of the model indicates that vortex unbinding is possible in this system, albeit in a very different way than the standard Kosterlitz-Thouless transition (which occurs in the absence of the transverse field.) Deconfinement occurs in a two step process, in which strings first proliferate, while the vortex-antivortex pairs remain bound by a residual attraction. With higher fluctuations the vortices may then fully unbind. The transitions are remarkably continuous, and challenge whether vortex unbinding in this system can be thought of as a true phase transition. Results of simulations supporting this picture will be presented.

The existence of both proliferated strings and deconfined vortices is significant for the bilayer quantum Hall system: their motion leads to time-dependence in the local spin angles and a resulting induced voltage via the Josephson relation $V \sim \frac{d\theta}{dt}$, resulting in dissipation. To assess the influence of these defects on dissipation in bilayer tunneling, we model the system as a large area resistively shunted Josephson junction, which we investigate numerically with Langevin dynamics. Fig. 1 illustrates the resulting tunneling resistivity of the system. For clean systems (inset), the resistance drops extremely rapidly with temperature, indicating that the strings and vortices become too dilute at low temperature to account for the dissipation seen in experiment. We then consider a dirty system, for which we find deconfined vortices and strings of overturned spins even in the low temperature state. This *string glass* state supports low energy excitations which can dissipate energy even at very low temperatures, leading to the greatly enhanced resistance apparent in the main panel of Fig. 1. Fig. 2 illustrates a low temperature snapshot of the string glass state, and shows that the localized excitations are associated with the deconfined vortices.

The model also indicates that the onset of "normal" dissipation occurs via a depinning transition of the strings, which should be accompanied by a peak in broadband noise. If observed experimentally, such noise would confirm the string glass nature of the system. Finally, we demonstrate that the model naturally explains why the zero bias conductance resonance persists in the presence of an in-plane magnetic field, as has been observed in experiment.

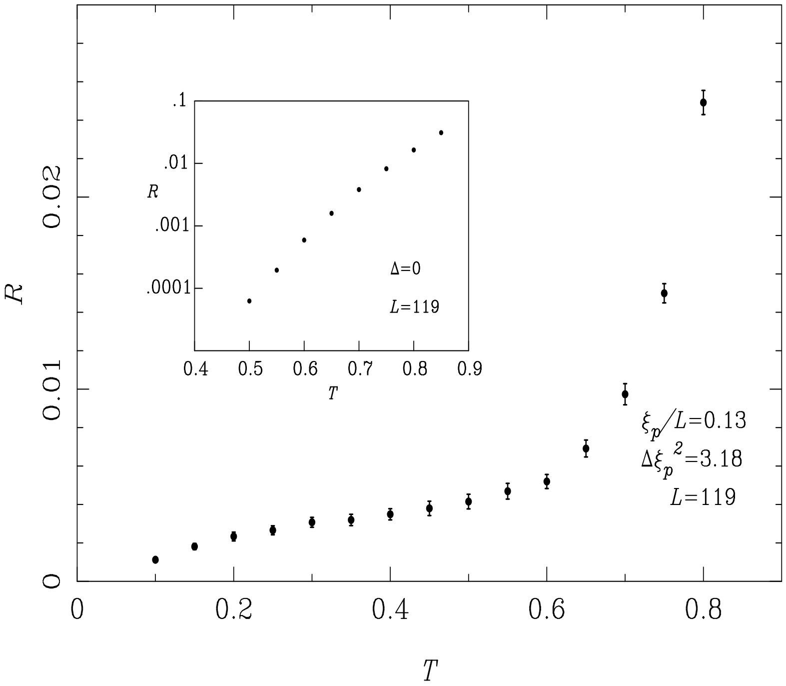

Figure 1: Tunneling resistance vs. temperature for a bilayer quantum Hall system modeled as a two-dimensional resistively shunted Josephson junction. Inset: Resistance in the absence of disorder, indicating a rapid vanishing of dissipation with temperature for clean systems. Main panel: Resistance in the presence of disorder, demonstrating a great enhancement of dissipation at low temperature, in qualitative agreement with experiment.

Figure 2: Snapshot from numerical simulations of a 79×79 lattice, with sufficient disorder to create unbound vortices and antivortices, as well as proliferated strings, in the low temperature (i.e., string glass) state. Only spins with $\cos\theta < 0$ are shown to allow imaging of the strings. Circles indicate the 100 most active spins, which are localized near vortices (+) and antivortices (∗), indicating that these support low energy, localized excitations.