Josephson Vortex Lattice Melting in Bi$_2$Sr$_2$CaCu$_2$O$_{8}$

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The Josephson vortex lattice state of the highly anisotropic high-T$_c$ superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8}$ has been probed by measurements of the out-of-plane (c-axis) resistivity as a function of temperature, current density, magnetic field strength H, and magnetic field orientation angle $\theta$. Anomalous dissipation is observed below a critical temperature identified as the melting transition of the Josephson vortex lattice. The critical T-H and T-$\theta$ phase boundaries are determined. The melting transition is interpreted as a Kosterlitz-Thouless depairing of interlayer vortex/anti-vortex pairs.

Crystals of Bi$_2$Sr$_2$CaCu$_2$O$_{8}$ (BSCCO-2212) were prepared using a traveling-solvent floating-zone (TSFZ) method described elsewhere$^1$. The crystals were cleaved to the desired dimensions, and electrical contacts were made using silver paint, fired at 650°C.

Samples were mounted on a cryostat which allowed in situ alignment with the magnetic field with an angular resolution of 0.013°. The cryostat was placed in the bore of a superconducting solenoid, allowing the measurement of the c-axis electrical resistivity of the samples as a function of temperature, current density, magnetic field strength H, and magnetic field orientation angle $\theta$.

Figure 1 shows the c-axis resistivity of a BSCCO-2212 sample in a field of 18 Tesla aligned parallel to the ab-plane for two measuring current densities. The general field-induced broadening below the superconducting transition temperature (T$_c$) is consistent with previous studies$^2$. However, the high and low current data diverge below a temperature T$_m$, where the low current data show a sharp kink. Electric field as a function of current density (E(J)) curves taken above and below T$_m$ show distinctly different behavior. For T$>$T$_m$, E(J) is always linear, but for T$<$T$_m$, E(J) is non-ohmic, displaying a well-defined critical current for the onset of dissipation with E$\sim$(J$-J_{\text{crit}}$) for J$>$J$_{\text{crit}}$ where J$_{\text{crit}}$ is the critical current.

The kink in the resistivity seen in Fig. 1 is reminiscent of the kink in both the in-plane
and c-axis resistivities versus temperature observed in YBa$_2$Cu$_3$O$_y$ (YBCO) crystals. It is noteworthy that in YBCO the dissipation kink is clearly observable at a current density of 4A/cm$^2$, while in the configuration described here for BSCCO the kink is only apparent at much lower current densities, on the order of $10^{-4}$ A/cm$^2$. In the case of YBCO, the kink corresponds to melting of the Abrikosov vortex lattice or glass, with E(J) characteristics ohmic above and non-ohmic below the melting temperature.

We propose that $T_m$ is the Josephson vortex lattice melting temperature in BSCCO-2212. $T_m$ is therefore expected to have unique functional dependencies on the magnetic field magnitude and orientation which distinguish it from the melting transitions of the conventional (H || c) vortex lattices in BSCCO-2212$^4$. We have repeated the measurements in Fig. 1 for different H field strengths and alignments to map out the T-H and T-0 phase boundaries.

Figure 2 shows the critical temperature $T_m$ needed to induce melting as a function of magnetic field angle $\theta$ with the ab-plane for a field of 7.5 Tesla. Anisotropic effective mass scaling theory, which predicts quite well the dependence of $T_m$ on $\theta$ in YBCO, cannot fit the data for BSCCO (dashed line). $T_m$ falls off too sharply with increasing field misalignment; phenomenologically, $H_m=H_m(0)\cdot A(H\sin\theta)^2$.

The $H_m(T)$ line also does not follow the expected form for three-dimensional vortex melting. Notably, we find $H_m(T)$ tends to zero at a temperature several Kelvin below $T_C$.

We propose$^6$ a model of a coupled Kosterlitz-Thouless and vortex lattice melting transition which can explain the H-0 and H-T phase diagrams. The Josephson vortex lattice is not expected to melt in the limit that the vortices are confined to lie in between superconducting planes$^5$. However, segments of Josephson vortex are expected to be thermally excited across the superconducting planes at finite temperature via creation of a Kosterlitz-Thouless vortex-antivortex pair. Above the Kosterlitz-Thouless transition temperature this pair is free to separate, and the vortices may cross the planes freely, so the Josephson lattice may melt. Below TKT, melting is forbidden.

TKT should be quickly suppressed with application of a perpendicular magnetic field, as we observe. Also, since TKT in zero field is a few Kelvin below $T_C$, we expect $H_m$ to tend to zero a few Kelvin below $T_C$ as observed.

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REFERENCES