Measurements of the Magnetic-Field-Tuned Conductivity of Disordered Two-Dimensional $Mo_{43}Ge_{57}$ and InO_{x} Superconducting Films: Evidence for a Universal Minimum Superfluid Response

S. Misra, L. Urban, M. Kim, G. Sambandamurthy, and A. Yazdani

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Measurements of the low-frequency ac conductivity of disordered two-dimensional $Mo_{43}Ge_{57}$ and InO_x superconducting films: evidence for a universal minimum superfluid response

S. Misra,[1] L. Urban,[1,2] M. Kim,[3] G. Sambandamurthy,[3] and A. Yazdani[1,*]

[1] *Joseph Henry Laboratories and Department of Physics, Princeton University*
[2] *Department of Physics, University of Illinois at Urbana-Champaign*
[3] *Department of Physics, University at Buffalo, The State University of New York*

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Our measurements of the low frequency ac conductivity in strongly disordered two-dimensional films near the magnetic field-tuned superconductor-to-insulator transition show a sudden drop in the phase stiffness of superconducting order with either increased temperature or magnetic field. Surprisingly, for two different material systems, the abrupt drop in the superfluid density in a magnetic field has the same universal value as that expected for a Berezinskii-Kosterlitz-Thouless transition in zero magnetic field. The characteristic temperature at which phase stiffness is suddenly lost can be tuned to zero at a critical magnetic field, following a power-law behavior with a critical exponent consistent with that obtained in previous dc transport studies on the dissipative side of the transition.

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In two dimensional (2D) systems, tuning localization by increasing disorder or applying a magnetic field drives a zero-temperature quantum phase transition between superconducting and insulating ground states [1]. Despite decades of effort, uncovering a variety of novel phenomena, including the discovery of the scaling of transport properties [2–5], unusual intervening zero temperature metallic phases [5–8], and insulators with localized pairs [9–12], the underlying mechanism for the superconductor-insulator transition continues to be debated [13, 14]. Experimentally, efforts to probe this transition have focused almost exclusively on DC transport measurements that probe the samples once they are already strongly dissipative. In contrast, ac conductivity measurements can probe the superconducting response of the system and directly detect the loss of superfluid-like response near the quantum phase transition out of the superconducting state, hence providing important complementary information.

In the absence of a magnetic field, ac measurements have played a key role in demonstrating that the loss of superconducting response in 2D superconductors with increasing temperature occurs below the mean-field transition temperature, T_{C0}, at the Berezinskii-Kosterlitz-Thouless (BKT) transition temperature, T_{BKT} [15, 16]. This transition occurs due to the unbinding of thermally generated vortex-anti-vortex pairs and is accompanied by a universal drop in the superfluid response of the system at T_{BKT}, which can be detected by ac measurements of the kinetic inductance [17, 18]. In relatively clean thin films, the application of a magnetic field gives rise to a pinned Abrikosov lattice, the melting of which through a dislocation-unbinding transition can also be detected using ac inductive measurements sensing sudden loss of lattice rigidity [19]. To date, the application of ac techniques to studying the superconductor-insulator transition in disordered systems has been limited to very high frequencies (very short length scales), where they have proven useful in detecting the remnant of superconducting correlations in the insulating phase [20].

In this letter, we use measurements of the low frequency ac conductivity to probe the loss of superconducting response in strongly disordered 2D films of $Mo_{43}Ge_{57}$ and InO_x as they are tuned close to a quantum phase transition out of the superconducting state with the application of a magnetic field. Our main experimental finding is that the loss of superconductivity as a function of magnetic field at a fixed temperature occurs via a universal drop in the superfluid response, with a value corresponding to that predicted for the BKT transition in zero field. Furthermore, we show that the temperature at which the superfluid response is suddenly lost can be tuned to zero at a critical value of the field, following a power-law behavior with a critical exponent consistent with that obtained in previous dc transport studies of the dissipative side of the transition [2–5]. Our results suggest that driving the energy scale associated with the minimum superfluid response to zero with a magnetic field results in the quantum transition out of the superconducting state, and into either an unusual zero temperature metallic phase or an insulator.

Typical measurements of the complex conductance and kinetic inductance using our two-coil mutual inductance technique [21] are shown Figure 1 for $Mo_{43}Ge_{57}$ samples in zero magnetic field. Figure 1a shows the in-phase and out-phase response of our pick-up loop in response to shielding currents excited in the thin film sample by a drive coil, along with DC resistivity measurements on the same sample. The pickup voltages can be numerically transformed to obtain the real and imaginary parts of the sheet conductance $G(\omega)$ [21], from which we compute the sample sheet impedance $Z(\omega) = R(\omega) + i\omega L(\omega)$, where $R(\omega)$ is the ac resistance and $L(\omega)$ is the ac inductance of the sample. The inverse inductance $L^{-1} = n_s e^2/m$, shown for example in Figure 1b for two different MoGe films in zero field, is proportional to the superfluid density n_s (m is the Cooper pair mass) and constitutes a direct measure of the phase stiffness of the superconducting order parameter in our samples.

Measurements in zero magnetic field demonstrate that our 2D samples undergo the expected vortex-anti-vortex unbinding BKT transition at which there is an abrupt loss of superfluid response at $T_{BKT} < T_{C0}$. As shown in Figure 1b, increasing the temperature results in a continuous decline in $L^{-1} = -\|\omega G\|^2/\Im[\omega G]$, which is well-defined up to the point where $\Im[\omega G]$ vanishes below our experimental noise floor ($\sim$.0005 nH^{-1}). At this temperature, we find $L^{-1} \sim n_s$ to approach a finite value just before superconductivity is lost in our sample. This behavior is similar to previous measurements of the superfluid density in other superconducting thin films [17, 18], as well as in two-dimensional superfluid films [22], and trapped Bose gases [23]. The sudden drop in the superfluid density is predicted to have a universal value, independent of microscopic details [24], which for superconducting thin films can be expressed as $L^{-1}(T_{BKT}) = n_s(T_{BKT})e^2/m = (8\pi/\Phi_0^2)k_B T_{BKT}$ (corresponding to a line with a slope of 0.081 nH^{-1}/K as shown in Figure 1b). The sudden change in our measured L^{-1}, shown in Figure 1b for two different MoGe films at low frequency, corresponds well to this predicted BKT universal jump and confirms that vortex anti-vortex unbinding underlies the loss of superconductivity in our samples in zero field with increasing temperature. Measurements at higher frequencies further confirm the shifting of the temperature at which L^{-1} vanishes toward the mean field transition T_{C0}, as expected for a BKT transition [25].

The application of a magnetic field strongly suppresses superconductivity in thin films, eventually driving the system through a quantum phase transition out of the superconducting state. Typically, dc resistivity measurements have been used to identify a critical value of the magnetic field B_X, where resistance isotherms cross each other and around which such data scales in a manner consistent with theoretical work on the superconductor-insulator transition [2–5]. However, resistivity measurements have also found a flattening of the resistance at the lowest temperatures in a field range close to B_X [6, 7], introducing the possibility of a metallic phase over an intervening range of magnetic field as the samples are driven from superconducting to insulating ground states. It is still debated whether such behavior is due to the lack of cooling of the samples rather than true metallic behavior. While such transport measurements, as shown for example in Figure 2a for our MoGe sample, directly

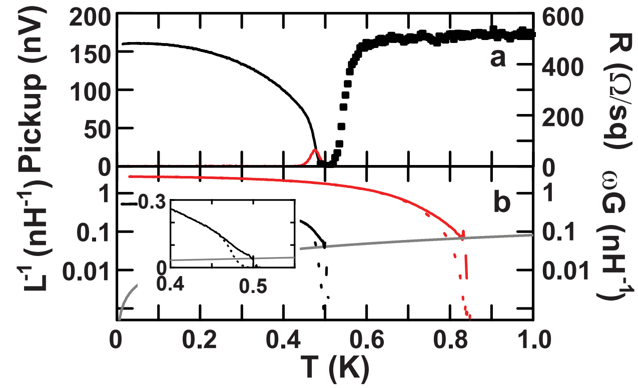

FIG. 1. (a) The in-phase (black) and out-of-phase (red) voltage on the pickup coil ($f = 20$ kHz and $I = 20$ μA on the drive coil), plotted along with the resistivity from conventional dc transport (black squares), is shown as a function of temperature at zero field for a MoGe film. (b) Plotted here is L^{-1} derived from the data in MoGe film in part (a) (black line), and a second less disordered film (red). Also shown are the imaginary part of ωG (dashed lines) and the BKT prediction for L^{-1} (gray). The inset shows a close-up of the data from the more disordered film on a linear scale.

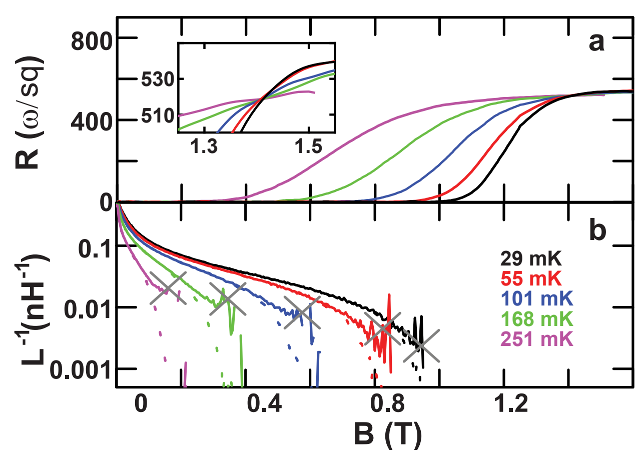

FIG. 2. (a) Measurements of dc resistivity isotherms, shown here for the MoGe sample in Figure 1(a) and taken at the indicated temperature, shown as a function of field. (inset) A close-up indicates that the isotherms cross at a field of $B_X = 1.41 \pm 0.02$T. (b) Measurements of L^{-1} isotherms for the same film as (a) taken at 50 kHz show a discontinuous jump which moves to larger values of the field at lower temperatures. Also shown are the imaginary part of ωG (dashed lines) and the BKT prediction for L^{-1} (gray crosses).

probe the changes of dissipation with magnetic field, they do not probe the loss of superfluid response. To obtain such information, we turn to our measurements of L^{-1} from the ac mutual inductance technique performed on the same sample, as shown in Figure 2b.

In general, application of a magnetic field alters the inductive response of a superconductor not only through the suppression of the superfluid density, but also through field-induced vortices. While detailed mod-

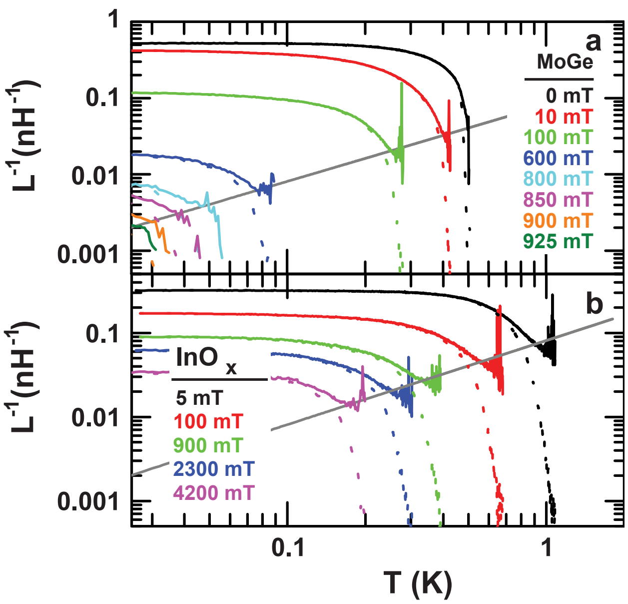

FIG. 3. Temperature sweeps of L^{-1}, taken here at 20 kHz, in the presence of an applied magnetic field show a discontinuous jump to zero in both (a) MoGe and (b) InO_x thin film samples. Also shown are the imaginary part of ωG (dashed lines) and the BKT prediction for L^{-1} (gray).

eling can be used to account for both these effects in L^{-1} [25], we focus instead on the point where the superfluid-like response is lost in our samples with increasing magnetic field. Remarkably, we find that at each temperature there is a specific value of field at which L^{-1} shows a precipitous drop to zero. The sudden loss of L^{-1} with field coincides with a sudden increase in dissipation that is first detected in the ac resistivity, and eventually can also be measured in dc transport [25]. The most intriguing aspect of the sudden loss of the superfluid response is that the value of the sudden drop corresponds to the same value for the universal jump in the superfluid density for the zero field BKT transition (crosses in Figure 2b). Moreover, with decreasing temperature, the characteristic field for the sudden change in superfluid-like response is continuously shifted to higher field.

A more accurate determination of the evolution of the sudden loss of superfluid response can be obtained by measuring the temperature dependence of L^{-1} at fixed values of the magnetic field. As shown in Figures 3a and 3b, such measurements on both MoGe and InO_x thin films show that the application of a field reduces the overall superfluid response of the sample at all temperatures, while increasing temperature results in a sudden loss of response abruptly at a temperature T^*. Our main experimental finding is that the jump in the superfluid density of strongly disordered 2D samples, whether field-tuned at a given temperature (Figure 2b) or temperature-tuned in the presence of a magnetic field (Figures 3a and 3b), follows the universal BKT value, independent of material system. Thus, surprisingly, the minimum strength of superfluid stiffness is determined by the zero-field BKT criterion, even in the presence of a magnetic field that introduces a sizable population of vortices. While the size of the jump becomes increasingly more difficult to measure at higher fields as T^* gets smaller, the size of the jump continues to follow the BKT criterion approaching the quantum phase transition.

It is important to recognize that the loss of superfluid response in our samples is distinct from earlier studies in cleaner 2D MoGe samples, which showed melting of the Abrikosov lattice via a dislocation-anti-dislocation unbinding transition [19]. Notably, the details associated with the pinning of vortices would be expected to differ between the two samples studied here, while a universal behavior of the superfluid response is measured. In addition, the loss of superfluid response at the 2D vortex lattice melting transition in cleaner thin films, although sudden, does not occur with the universal BKT value [19]. Finally, as shown previously, increasing the disorder through decreasing film thickness, and hence suppressing the zero-field superconducting transition temperature significantly compared to thick (3D) films, results in the eventual disappearance of the experimental signatures of vortex lattice melting since pinning and creep dominates the behavior of a glassy vortex system [26]. Not only do the MoGe and InO_x samples examined here have zero-field superconducting transitions which are dramatically suppressed in comparison to thicker films (for example, 500 mK for the MoGe film here, compared to 1.05 K for a thicker film close to bulk T_c), but they also show a frequency dependence at finite field which is consistent with vortex creep [25], both of which indicate they should have an extremely disordered vortex lattice. The superfluid response of such disordered thin films has never been previously probed at low frequencies approaching the field-tuned quantum phase transition out of the superconducting state.

To determine the connection between the loss of superfluid response and possible quantum phase transitions in our strongly disordered thin films, we examine the behavior of T^* as a function of magnetic field. As shown in Figure 4, the temperature T^* at which superfluid response is lost extrapolates to zero, suggesting the presence of a quantum phase transition at a critical value of the magnetic field where superconducting behavior is lost at zero temperature. We find that simple extrapolation of the data, shown in Figure 4, to zero temperature finds a critical field ($B^* = 1.2 \pm 0.1$T) that, despite a significant error bar, is smaller than the crossing field extracted from resistance isotherms such as those shown in the inset of Figure 2 ($B_X = 1.41 \pm 0.02$T). Limited frequency-dependent data taken at our base temperature imply that the superconducting phase could terminate at fields even lower than B^* in the zero-frequency limit [25]. This discrepancy between B^* and B_X may in fact be due

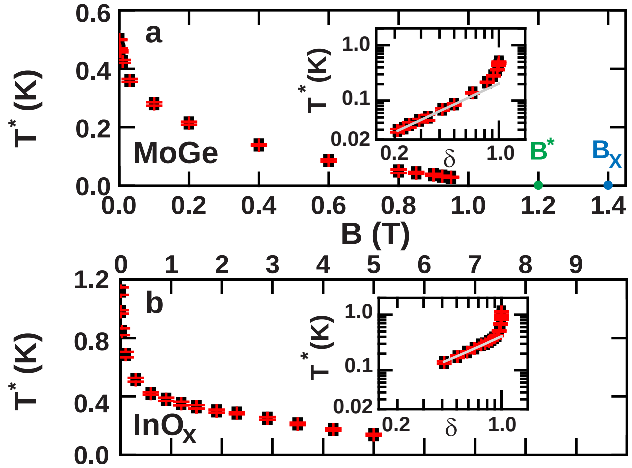

FIG. 4. Shown are the temperatures (T^*), along with error bars (red lines), at which L^{-1} is measured to jump to zero in our temperature sweeps at fixed field in the (a) MoGe and (b) InO_x samples (f = 20 kHz). The inset shows a fit of the data to the power law form $T^* \sim \delta^{\nu z}$, where $\delta = (1 - B/B^*)$ on a log-log scale. In part (a), the fitted critical field B^* from the ac measurements is shown in green, along with the crossing field B_X from the resistivity data of Figure 2 in blue.

to the presence of an intervening metallic phase that has no superfluid response, but has finite resistance even in the limit of zero temperature [7]. We proceed to explore if the vanishing T^* has properties consistent with that of a quantum critical point, near which we anticipate that $T^* \sim (1 - B/B^*)^{\nu z}$, where νz are exponents governed by the critical fluctuations near the quantum phase transition [27, 28]. The inset of Figure 4 shows the extracted value of T^* as a function of magnetic field, and the corresponding power-law fits near where T^* approaches zero to obtain B^* (1.2 ± 0.1T for MoGe and 8.5 ± 1.5T for InO_x) and the combination of critical exponents νz (1.25 ± 0.25 for MoGe and 1.3 ± 0.4 for InO_x). It is interesting to note that, despite significant error bars, these critical exponents are consistent with transport studies on similar MoGe and InO_x samples, when these studies have limited their analysis to exclude resistivity data showing finite dissipation extrapolating to zero temperature [2, 4, 5, 7].

Our measurements demonstrate that the loss of superfluid response in a disordered 2D superconductor in the presence of a field is surprisingly well-described by the BKT criterion for minimum sustainable superfluid response familiar from other 2D superfluid-insulator or superfluid-normal transitions, despite the presence of a net vorticity resulting from the external magnetic field. Following the characteristic jump in the superfluid response with field and temperature, we arrive at the conclusion that the energy scale associated with this minimum superfluid response is driven to zero at a critical value of the magnetic field. In the absence of a magnetic field, the idea that a vortex-anti-vortex unbinding mechanism, such as that demonstrated for our films at finite temperature (Figure 1), can underlie the quantum phase transition out of the superconducting state has been previously considered when the transition is driven by disorder [13]. Increased disorder suppresses the overall superfluid density, while the minimum sustainable superfluid density is still described by the vortex-anti-vortex unbinding criterion, resulting in a continuous tuning of T_{BKT} to zero. Extending this interpretation to our results is complicated by the simple fact that the applied field changes the energetics of vortices versus anti-vortices, and one usually considers the loss of superconductivity in the context of melting of the Abrikosov vortex lattice via dislocation-anti-dislocation unbinding rather than vortex-anti-vortex unbinding. In contrast, our experiments are in the limit of a strongly disordered vortex lattice, where pinning and creep of vortices in a glassy state dominates over melting phenomena associated with that of a clean system.

A key question our experiments raise is whether mechanisms other than vortex-anti-vortex unbinding can result in a minimum superfluid density criterion similar to that of the BKT transition. Understanding the universality of our minimum sustainable superfluid response in the strongly disordered samples studied here could provide the context to have a unified explanation of the destruction of superconductivity at zero temperature both as a function of disorder and magnetic field.

* yazdani@princeton.edu

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