Novel Vortex Distribution in the $\beta$-Pyrochlore Superconductor KOs$_2$O$_6$

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Abstract. By utilizing the micro-Hall probe array, we study the superconducting and the vortex states in a single crystal of KOs$_2$O$_6$ near the first-order transition at $T_p \sim 8$ K, which is associated with a change in the rattling motion of K ions. We show that below the first-order transition, the lower critical field exhibits a distinct decrease, suggesting that the electron-phonon coupling is weakened below the transition. At high magnetic fields, the local magnetization shows an unexpectedly large jump at $T_p$ with a sign change near the sample edges. Our results demonstrate a novel redistribution of vortices whose energy is reduced abruptly below the first-order transition at $T_p$.

1. Introduction

In the recently discovered $\beta$-pyrochlore superconductor KOs$_2$O$_6$ [1, 2], having the highest superconducting transition temperature $T_c = 9.6$ K among pyrochlores, an intriguing first-order transition in the superconducting state has been observed below $T_c$ [2, 3, 4] and its relation to the anomalous “rattling” motion of K ions [5, 6] has attracted much interest. How this transition affects the superconductivity and the vortex state in the presence of magnetic fields is a fundamental physical problem yet to be clarified.

From the micro-Hall probe array magnetometry, we observed a number of remarkable anomalies of vortex state associated with the first-order transition [7]. Below the first-order transition at $T_p \sim 8$ K, the lower critical field shows a distinct decrease, suggesting that the electron-phonon coupling is weakened below the transition. At high magnetic fields, the local magnetization shows an unexpectedly large jump at $T_p$ with a sign change near the sample edges. Our results demonstrate a novel redistribution of vortices whose energy is reduced abruptly below the first-order transition at $T_p$.

2. Experimental

KOs$_2$O$_6$ single crystals were grown by the technique described elsewhere [2]. We measure the local induction $B_{\text{local}}$ by using a sensitive Hall-sensor array tailored in a GaAs/AlGaAs two dimensional electron gas system. Each sensor has an active area of $6 \times 6 \ \mu$m$^2$, and the center-to-center distance of neighboring sensors is $20 \ \mu$m. A KOs$_2$O$_6$ crystal with dimensions $110 \times 270 \times 90 \ \mu$m$^3$ is placed on top of the array; the magnetic field $H$ is applied along the
90 μm direction by using a low-inductance 1.8-T superconducting magnet with a negligibly small remanent field.

3. Results and Discussion
In Fig. 1(a) we show the field dependence of “local magnetization” defined by $B_{\text{local}} - H$. At the first penetration field $H_{fp}$, a sharp dip (or peak) is observed. This indicates that the small hysteresis is governed by geometrical (surface) barriers [8, 9] and the contribution of bulk pinning in this system is quite small. In such a case, the lower critical field $H_{c1}$ can be determined from the expression for the first-penetration field of a superconducting bar, accounting for the demagnetization effect: $H_{fp}/H_{c1} = \tanh(\sqrt{b/a})$, where $b/a$ is aspect ratio of the bar, with the perpendicular field along the thickness $2b$ [9]. From this, we evaluate $H_{fp}/H_{c1} = 0.50$ and thus we obtain $H_{c1}(T)$ as depicted in Fig. 1(b). The obtained slope shows thermodynamic consistency with other reports [4, 10]. It is clear that $H_{c1}(T)$ below $T_p \sim 8$ K is lower than that extrapolated from higher temperature data. Since the low temperature data extrapolates to a temperature $T_0 = 9.2$ K, lower than $T_c$, the relative decrease in $H_{c1}$ immediately indicates that the effective transition temperature is reduced below $T_p$. This is reinforced by the consistent results in recent measurements of the penetration depth $\lambda(T)$ [11], in which a similar shift of the superfluid density $\lambda^{-2}(T)$ to a lower value is observed below $T_p$. These results indicate that below $T_p$, the effective $T_c$, the superconducting gap, and the condensation energy become smaller. Since there is growing evidence for fully gapped superconductivity [11, 12, 13] which favors phonon-mediated pairing, the obtained result suggests that the electron-phonon coupling strength is weakened below $T_p$ [14].

Next, let us discuss the higher field measurements. Recent global magnetization measurements revealed a jump at $T_p$ in the total induction $\Delta B \sim 0.5$ G at 2 T [4]. In sharp contrast, the local induction $B_{\text{local}}(T)$ exhibits a much larger jump at $T_p$. In Fig. 2(a) we plot the change of the local induction $\delta B_{\text{local}}(T)$ relative to the normal state near the center of the sample. With decreasing temperature, $\delta B_{\text{local}}$ becomes negative below $T_c(H)$ and decreases down to $T_p$. At $T_p$, there is a jump with field-dependent magnitude up to $\sim 8$ G, which is more than an order of magnitude larger than the global jump. Remarkably, the behavior of the $\Delta B_{\text{local}}$ jump at $T_p$ strongly depends on the position at which it is measured on the samples.
Near the center, $\delta B_{\text{local}}(T)$ increases abruptly below $T_p$ [Fig. 2(a)], but it jumps to an opposite direction near the edge [Fig. 2(b)].

To clarify this anomalous jump at the transition, we plot the position dependence of $\delta B_{\text{local}}$ in Fig. 3. Above $T_p$ [Fig. 3(a)], the induction profile shows the standard behavior. Just below $T_p$, the field distribution has drastically changed, especially at high fields [Fig. 3(b)]: the vortex density profile now has a characteristic dome-like shape with troughs away from the center.

Finally, we discuss the possible mechanism of this novel vortex redistribution considering vortex energy change below $T_p$. The free energy of a single vortex per unit length $\varepsilon = \ldots$

**Figure 2.** Temperature dependence of the local induction change with respect to the value in the normal state, for different applied fields near the crystal edge (a) and near the center (b).

**Figure 3.** Local induction change as a function of position just above (a) and below $T_p$ (b).
\[
\left( \frac{\Phi_0}{4\pi} \right)^2 \ln \kappa = \frac{\Phi_0}{4\pi} H_{c1}
\]
becomes smaller in the low-temperature phase, because of the relative reduction of \(H_{c1}\) as observed in Fig. 1. At the first-order transition, the low-\(T\) phase and high-\(T\) phase coexist, and the region of the low-\(T\) phase is invested by “cheaper” vortices with smaller \(\varepsilon\). Then vortices near the boundaries between the two phases should be attracted to the low-\(T\) phase region. This mechanism promotes inhomogeneous vortex density: denser in the low-\(T\) phase and sparse in the high-\(T\) phase regions. In this way, we may have the dome-shaped vortex distribution resembling the situation discussed in the presence of the geometrical surface barriers [8].

4. Summary
In summary, a Hall sensor array was used to detect magnetic induction locally in the superconducting and vortex states of a single crystal of the \(\beta\)-pyrochlore superconductor \(\text{KOs}_2\text{O}_6\) presenting a first-order transition within the superconducting state. Below the first-order transition temperature \(T_p\), the lower critical field is shifted down, and the local induction reveals large jumps which depend on the position inside the sample. We found an abrupt vortex redistribution into a flux dome, which we believe decorates the nucleating low-temperature phase. Our results indicate that the change in the rattling motion reduces the superconducting critical fields as well as the vortex energy.

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