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Extreme magnetic field-boosted superconductivity

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Supplemental material: Extreme magnetic field-boosted superconductivity

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I. SC_{RE} PHASE IN *bc* PLANE

We did not observe the SC_{RE} phase for θ larger than 3.9° in the *bc*-plane. It is very likely that this is the angle limit of the SC_{RE} phase. The magnetoresistance data show a slope change between 20 and 30 T for $\theta = 3.9°$ (Fig. 1), indicating it is on the edge of SC_{RE} phase.

II. ANGLE OFFEST IN PULSED FIELD MEASUREMENTS

In order to detect the magnetic transition at higher angles, we had to perform experiments in pulsed field, where a probe compatible with a two-axis rotator is not available. Therefore, when the magnetic field rotates in one plane (e.g., *ab*-plane), there generally is a small angle offset in the perpendicular plane (e.g., *bc*-plane). This is probably why the field range of SC_{PM} looks smaller in pulsed field compared to the value in our previous paper[1], and SC_{RE} is not observed, in both magnetoresistance and PDO measurements. In addition, the base temperature in pulsed field, 0.5 K, is higher than that of the DC field, 0.35 K. For these reasons, pulsed field data are not used to characterize the SC_{PM} and SC_{RE} phases.

The field polarized state and SC_{FP} phase extends to very high fields, beyond the limit of DC field, and therefore the pulsed field measurements are the only choice to characterize both phases, which inevitably gives some angle offset. This angle offset, of order a few degrees, explains the slight difference between the phase diagrams based on PDO and magnetoresistance measurements.

III. HYSTERESIS IN PDO AND MAGNETORESISTANCE

The high-field induced superconducting phase can be seen in both PDO and magnetoresistance measurements in the downsweeps of the pulsed magnetic fields. The PDO frequency is larger on the high-field side of the transition, corresponding to a decrease in sample resistance[2–4]. Similarly, in decreasing field, the magnetoresistance is lower above the transition. However, the PDO frequency drops (suggesting higher resistance) at the transition during upsweeps of the magnetic field, leading to a large hysteresis loop. A qualitatively similar hysteresis is observed in the magnetoresistance. However, the hysteresis in magnetoresistance decreases with increasing angle from *b* towards the *c*-axis and almost disappears for $\theta = 24°$.

The hysteresis is likely to be due to sample heating during the upsweep of the pulsed magnetic field. There are three possible causes: (i) eddy currents in the normal state induced by rapidly changing fields; (ii) a magnetocaloric effect associated with the magnetic transition close to the onset of the field-induced superconductivity[5]; and (iii) heating due to vortex motion as the low-field superconducting state is traversed. In the 65 T magnets, the rise time to full field is about 9 ms, whereas the fall from maximum to zero field lasts about 90 ms[5]. Hence $\mathrm{d}B/\mathrm{d}t$ is much larger as the field increases. Inductive heating due to eddy currents is proportional to $(\mathrm{d}B/\mathrm{d}t)^2$ and so the sample is likely to be relatively hot during the upsweep. Additional magnetocaloric heating is likely to occur as the sample traverses the magnetic transition. Finally, the fact that the apparent upper critical field of the low-field superconducting state is much lower on the upsweep of the field is suggestive of heating due to vortex motion[6], though this contribution to the overall warming of the sample may well have thermalized by the time the magnetic transition is reached.

To ameliorate these effects, sample sizes are kept (i) small to present very little cross-sectional area to the field (thereby minimizing eddy-current heating) and (ii) thin to provide a large surface area-to- volume ratio to maximize cooling. In addition, rapid thermalization is assisted by using a relatively high pressure of 4He exchange gas. Finally, as mentioned above, during the down- sweep, $\mathrm{d}B/\mathrm{d}t$ is significantly smaller than during the up-sweep, further reducing any residual eddy-current heating and giving the sample time to thermalize[6]. Based on comparable measurements of other systems in pulsed fields[5,6], we believe that the sample is essentially in equilibrium with the thermometer when it exits the field-induced superconducting state on the way down, leading to an accurate measurement of the transition. Therefore, we use the down-sweep data for determining the phase diagrams.

In PDO measurements, we also observed hysteresis for $\theta = 0°$. This may be associated with the magneto caloric effect on traversing the magnetic transition.

IV. CRITERIA TO DETERMINE THE CRITICAL FIELDS

In order to construct the phase diagram with consistent critical field values, the following criteria are used to extrapolate the critical fields of various phases: for magnetoresistance measurements, we use the field at which the maximum slope of the resistance data that goes to zero resistance extrapolates to zero resistance (Fig. 4a and b); for PDO measurements, we use the field at which the maximum in derivative occurs (Fig. 4c and d).

V. MAGNETIZATION MEASUREMENTS

The magnetization measurement was performed with the magnetic field applied at $\theta = 35°$ from b towards c-axis, where the SC_{FP} phase was observed in magnetoresistance and PDO measurements. Similar to what seen for field along b-axis, the magnetic moment jumps from 0.4 to 0.7 μ_B, indicating a field polarized state in the high magnetic field.

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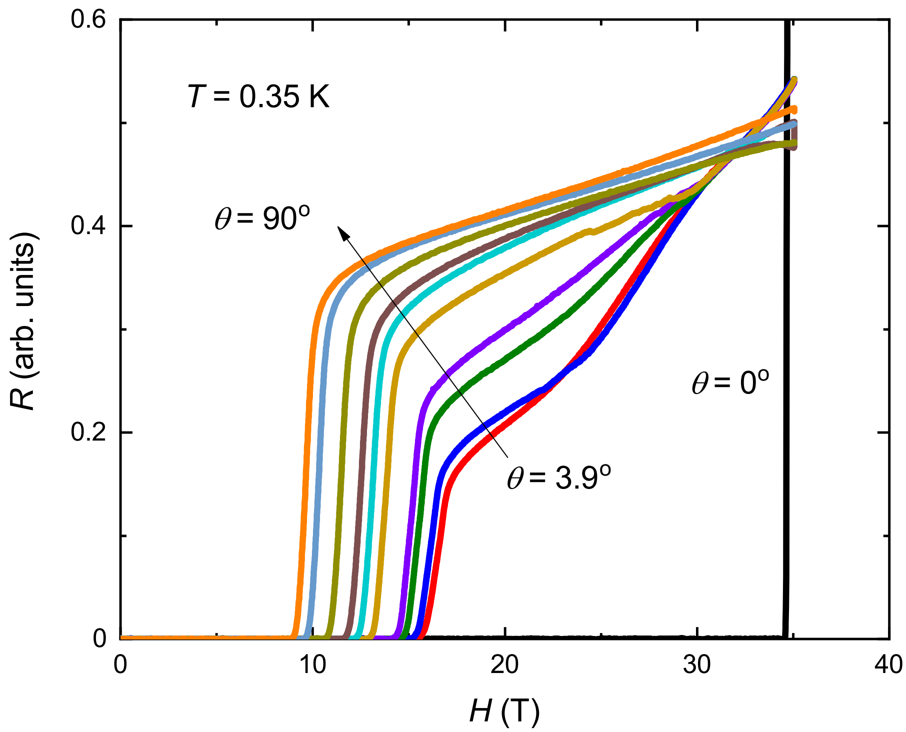

FIG. 1. Field dependence of magnetoresistance of UTe_2 at $T = 0.35$ K measured in the DC field. The magnetic field is rotated from b towards c axis. Zero resistance persists up to 34.5 T when the magnetic field is perfectly along b-axis. Reentrance of superconductivity is not observed when the magnetic field is rotated from b towards the c-axis.

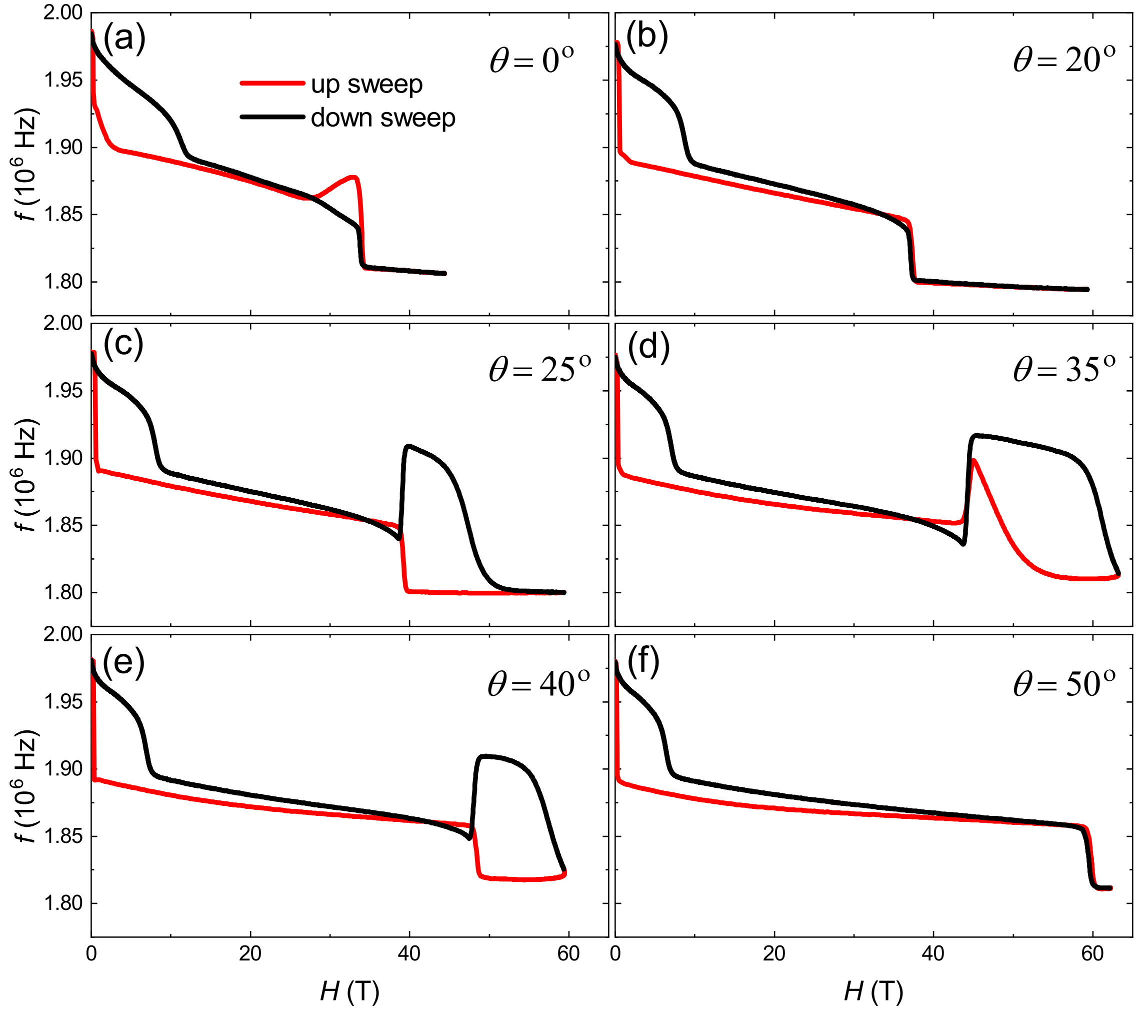

FIG. 2. PDO measurements of UTe_2 at $T = 0.45$ K in the pulsed field, for magnetic field applied at various angles from b towards the c-axis

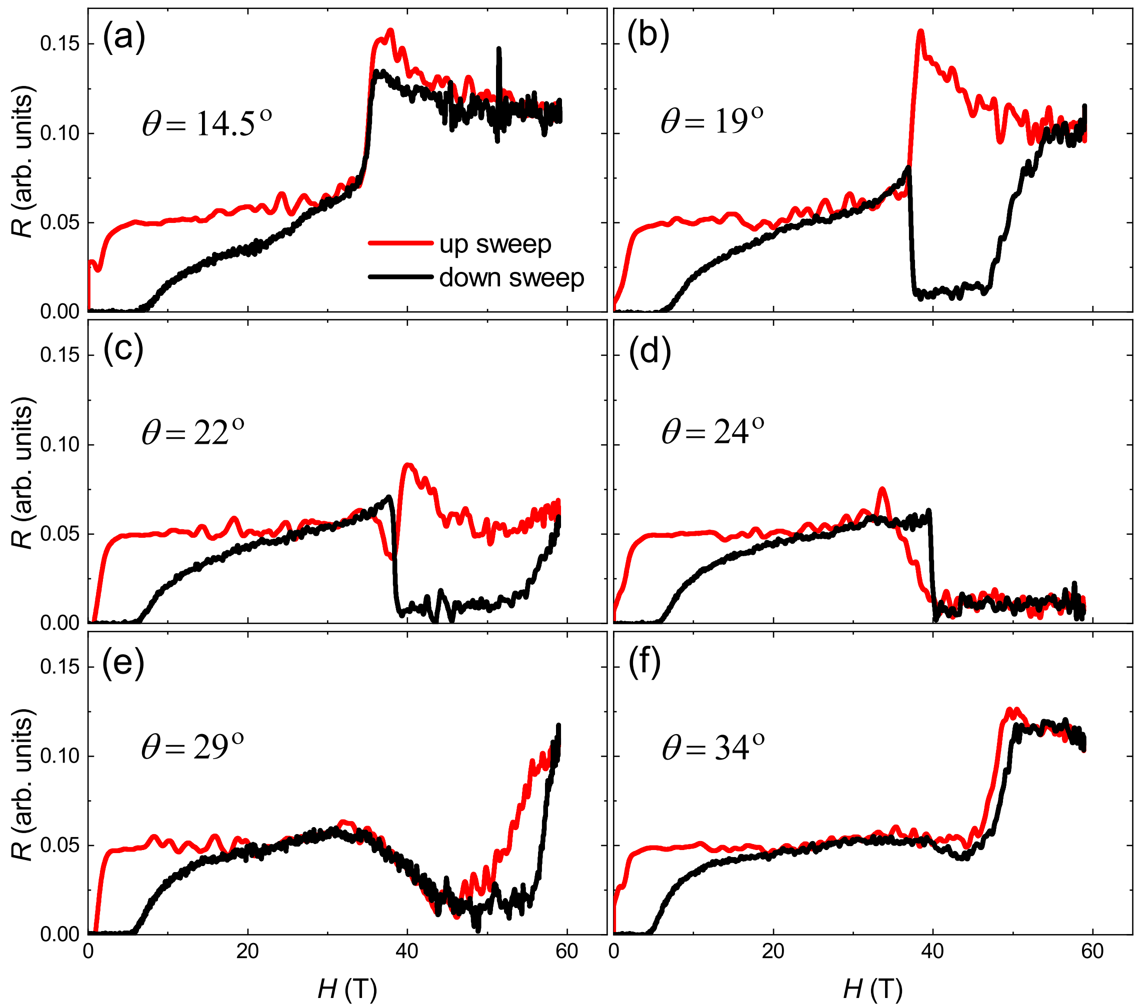

FIG. 3. Magnetoresistance measurements of UTe_2 at $T = 0.45$ K in the pulsed field, for magnetic field applied at various angles from b towards the c-axis.

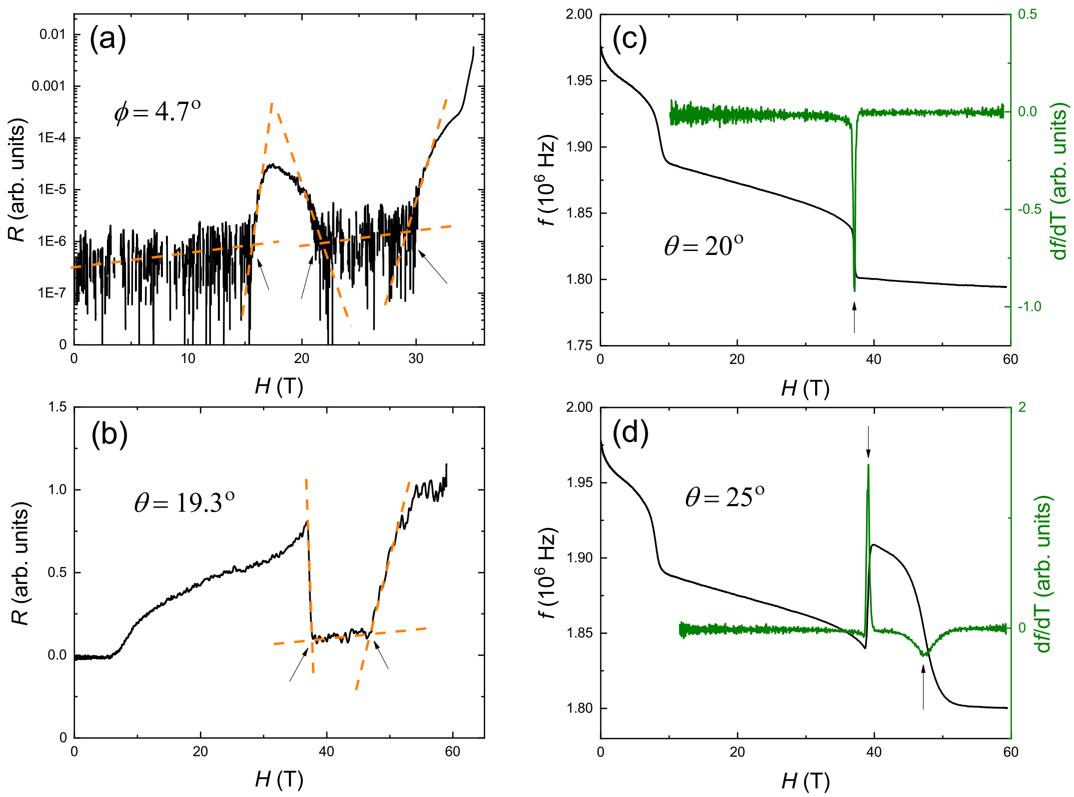

FIG. 4. Selected magnetoresistance (a nd b) and PDO (c and d) measurements to show the criteria used to extrapolate the critical field values for various phases.

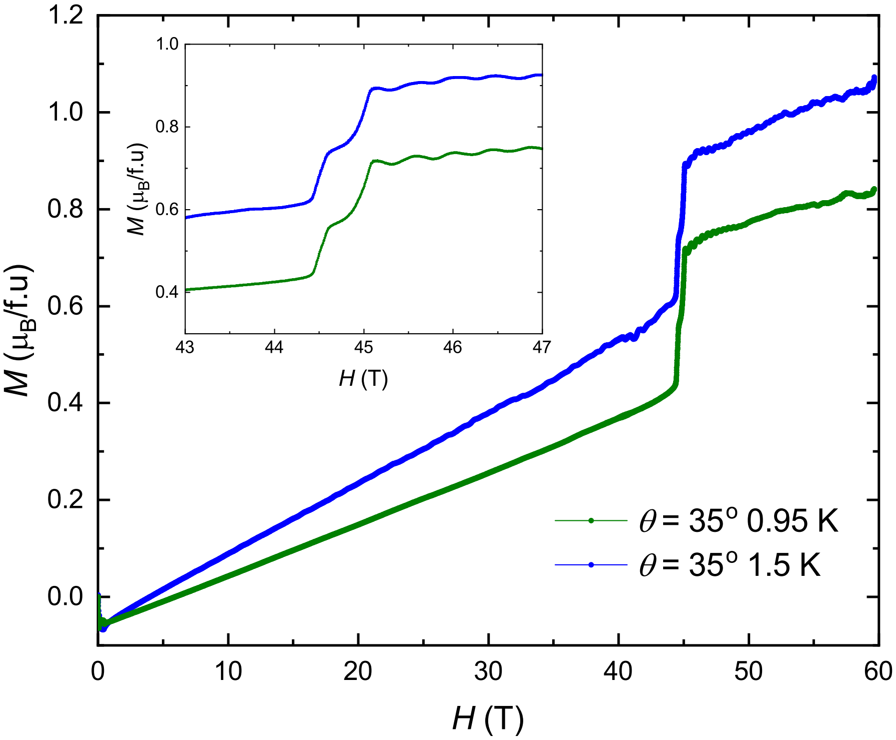

FIG. 5. Magnetization measurements UTe_2 at $T = 0.95$ K and 1.5 K in the pulsed field, with the magnetic field applied at $\theta = 35°$ from b towards c-axis.