Asymmetric Avalanche Behavior in a Zeeman-Limited Superconductor

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Abstract. We have performed transport and tunneling density of states measurements of ultra-thin Al films through the first-order parallel critical field transition. The transition is intrinsically hysteretic and exhibits avalanche-like jumps in both resistivity and tunneling density states. Tunneling measurements on films with sheet resistances of a few hundred ohms show large avalanche-like collapses of the condensate on the superheating branch of the critical field hysteresis loop. In contrast, the transition back into the superconducting phase (i.e., along the supercooling branch) is always continuous.

1. Introduction

The response of a superconductor to a magnetic field that only couples to the electron’s spin, sometimes referred to as a Zeeman field, remains a subject of significant interest [1, 2]. In practice, if one applies a magnetic field to a superconducting film whose thickness is much less than the coherence length, then the primary coupling between the field and the condensate is through the Zeeman splitting of the conduction electrons. The film geometry suppresses the Miessner response and the parallel field cannot induce screening currents, nor can quantized vortices enter the system. In this limit, the critical field transition is Zeeman mediated. Studies of Zeeman-limited superconductivity in low atomic mass elemental metal films have revealed several interesting effects, including a hysteretic first-order critical field transition [3, 4], incoherent Cooper pairing [4, 5], reentranse [6], and excess sub-gap states [7]. Here, we present resistivity and tunneling density of states measurements across the hysteretic Zeeman critical field transition in ultra-thin Al films. As the normal state is approached, we observe large avalanches in the density of states indicating that macroscopic regions of superconductivity suddenly and irreversibly collapse. In contrast, the transition from the normal state to the superconducting state is smooth and continuous.

In this study a magnetic field was applied parallel to the surface of superconducting Al films having a thickness that was approximately 5 times smaller than the coherence length ($\xi \sim 20$ nm). In this limit, the orbital response to the field is suppressed, and the transition occurs when the Zeeman splitting is of the order of the superconducting gap $\Delta_0$ [8]. The conventional picture is that this Zeeman mediated transition, which is often referred to as the spin-paramagnetic (S-P) transition, occurs between a BCS ground state with a homogenous order parameter and a polarized Fermi liquid normal state. At low temperatures the Zeeman critical field is expected to be near the Clogston-Chandrasekhar value $H_c = \Delta_0/\sqrt{2}\mu_B$ [9]. As we show below, the
non-equilibrium behavior of the Zeeman-limited superconducting ground state suggests that the order parameter may not be homogeneous.

### 2. Sample Preparation

Samples were fabricated by first preparing aluminum films from 99.999% Al targets via e-beam deposition onto fire-polished glass substrates held at 84 K. The deposition rate was typically 1 Å/s in a 0.1 µTorr vacuum. Films with thicknesses ranging from $t = 20 \rightarrow 30$ Å had normal-state sheet resistances that ranged from $R_n = 5.5$ kΩ/sq to 80 Ω/sq at 80 mK, respectively, and a disorder-independent superconducting transition temperature of $T_c \sim 2.7$ K. After the initial deposition, the films were warmed to room temperature and then exposed to air for 10-20 min in order to form a thin native oxide, which served as the tunneling barrier. A 90-Å-thick Al counter-electrode was deposited on top of the oxide thereby creating a junction with an area of about 1 x 1 mm$^2$. The barrier resistances ranged from 1 kΩ to 10 kΩ depending on the thickness of the electrode, exposure time, and other factors. Only junctions with barrier resistances much higher than the films’ resistance were used. Transport and tunneling data were collected via a 4-probe configuration with a lock-in amplifier. The films were cooled using a dilution refrigerator equipped with a mechanical rotator allowing us to align the films to within 0.1° of parallel field.

### 3. Experimental Results

![Figure 1](image1.png)  
**Figure 1.** Parallel critical field transition in a $R_n = 570$Ω/sq Al film at 60 mK. The red and black lines represent two identical sweeps through the first-order transition. The arrows depict the field sweep direction.

![Figure 2](image2.png)  
**Figure 2.** Parallel critical field transition for the film in Fig. 1 taken at two different sweep rates.

Shown in Fig. 1 is the resistive parallel critical field transition of a $R_n = 570$Ω/sq Al film, taken at 60 mK. The data represent two identical sweeps through the hysteretic transition. Note that the upsweep branch (superheating branch) of the hysteresis loop is interspersed with many avalanche-like jumps in resistance, whereas the down sweep branch (supercooling branch) is somewhat smoother. These jumps are similar to what has been observed in previous transport studies of Al films having substantially more disorder than the ones used in this study [5, 6]. Since the film thicknesses is much less than the coherence length, the jumps are not due to superconducting vortex motion nor to magnetic flux dynamics.
The non-equilibrium character of the hysteresis loop has both field dependent and time dependent components. In Fig. 2 we show two loops that were obtained using different field sweep rates. Note that intervals between the avalanches on the superheating branch are much flatter in the 20 G/s trace that they are in the 2 G/s trace. This clearly indicates that there is a slow temporal relaxation between avalanches. We have probed the time dependence of the transition by halting the field sweep at the midpoint of the superheating branch and then measuring the ensuing relaxation. Generally, such traces follow a stretched-exponential form with occasional spontaneous avalanches. Although transport measurements leave little doubt that avalanche-like dynamics is characteristic of the S-P transition, it has remained unclear whether or not the non-equilibrium behavior observed in transport actually represents the behavior of the condensate. For example, a sample that is almost entirely in the normal state can still have zero resistance so long as there is at least one superconducting filamentary path along its length.

Figure 3. The zero bias tunneling conductance normalized by its normal state value. The data was taken on a $R_n = 570 \, \Omega/\text{sq}$ Al film as a function of parallel magnetic field at $T = 60 \, \text{mK}$. The red and black lines represent two separate sweeps through the hysteresis loop. The arrows depict the field sweep direction.

Figure 4. Normalized tunneling density of states of the film in Fig. 3 showing the parallel critical field hysteresis loop for two different sweep rates. These data were taken at 60 mK.

At low temperatures the quasiparticle tunneling conductance is proportional to the density of electronic states (DOS) of the superconducting films [13]. Since planar tunneling is an areal microscopic probe of the condensate, it is relatively insensitive to filamentary superconductivity. Indeed, previous tunneling studies of the S-P transition have shown that the order parameter exhibits a hysteresis that is very similar to what is observed in transport, but up to now avalanches have not been reported in such spectra [9]. Shown in Fig. 4 is the zero-bias tunneling conductance of the film used in Fig. 1 as a function of parallel field. Because the Al counter-electrode was relatively thick, it had a critical field ($\sim 3 \, \text{T}$) that was much lower than that of the film. Thus the data in Fig. 3 represent S-I-N tunneling and reflect the quasiparticle density of states at the Fermi energy of the Al film. The precipitous drop in tunneling conductance as the field is lowered through the transition is due to the opening of the superconducting gap. Note that the superheating DOS exhibits avalanche behavior, but the supercooling branch is smooth and continuous. Similar behavior was observed in all of our moderately disordered samples.

The asymmetry of the avalanches in Fig. 3 is unusual. For instance, avalanches in the
magnetization of ferromagnetic systems (Barkhausen effect) are observed on both branches of the magnetization loop [15, 16]. Similarly, avalanches are observed in Martensitic transitions when the sample is either cooled or heated through the transition [17]. In Fig. 4 we show the effects of sweep rate on the hysteresis loop obtained from the zero bias tunnel conductance. The 20 G/s hysteresis loop is slightly wider than the 2 G/s loop, as is expected. But otherwise, the two loops look very similar to each other.

4. Summary
We observe avalanche-like collapses in the condensate on the superheating branch of the S-P transition hysteresis loop of moderately disordered Al films. Our data suggest that as the magnetic field is lowered through the parallel critical field, the system can always find an appropriate ground state that can accommodate the pairing interaction, Zeeman field, and the disorder. Hence, the supercooling branch is smooth and continuous. But, for reasons that remain unclear, the system cannot find a continuous path from the superconducting phase to the normal state. One possible explanation for the asymmetric avalanche behavior is that the high-field order parameter is more complex than that of a homogeneous BCS ground state.

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