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Two kinds of vortex states in thin mesoscopic superconductors

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Abstract. Experimentally, multivortex states and giant vortex states in mesoscopic superconductors can be distinguished directly by using the multiple-small-tunnel-junctions, and indirectly by studying the temperature dependence of the expulsion fields. These experimental results are compared with the theoretical prediction from the nonlinear Ginzburg-Landau theory.

1. Introduction

Mesoscopic superconducting disks have sizes comparable to the coherence length and/or the penetration depth . Vortex states in such mesoscopic disks attracted a lot of attention, both theoretically (see e.g. Ref. 1) and experimentally (see e.g. Ref. 2). Theoretically it was predicted that two types of vortex states can nucleate in mesoscopic disks: (i) a giant vortex state (GVS) where the order parameter has a single zero with a winding number (or vorticity) L and (ii) a multivortex state (MVS), which is the finite-size version of the Abrikosov vortex lattice. However, for a long time there was no *direct* experimental proof for the existence of these two types of vortex states in mesoscopic disks.

Recently, we were able to experimentally distinguish between MVSs and GVSs in mesoscopic superconducting disks, by using the multiple-small-tunnel-junctions method (MSTJ)[3], in which several small tunnel junctions with high tunnel resistance are attached to a mesoscopic superconductor in order to detect small changes in the local density of states, and therefore the supercurrent, under the junctions. It became also possible to observe experimentally transitions from a GVS to a MVS and transitions between different MVSs. All the experimental results were supported by the theoretical prediction in the framework of the nonlinear Ginzburg-Landau theory.

Alternatively, we showed later that it is also possible to obtain information about the type of the vortex state by studying the temperature dependence of the expulsion fields[4]. When, just before one vortex is expelled, the vortex state is a MVS, then the expulsion fields are almost temperature independent. In fact, they decrease slightly. When this last state is a GVS, then the expulsion fields increase with increasing temperature.

In the present paper, we give a brief overview of the two methods.

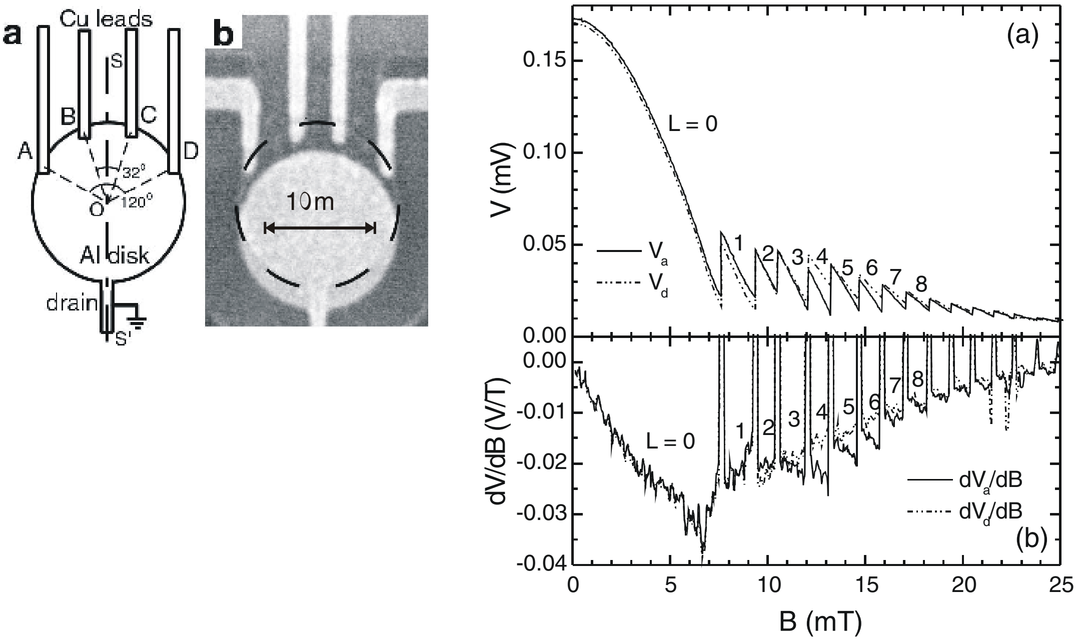

Figure 1. (left) The sample. (a) Schematical representation. (b) Scanning electron micrograph of a disk sample. (right) (a)Variation of voltages for junction pairs at symmetrical positions, A and D, in a decreasing field. The current through each junction is 100 pA and the temperature is 0.03K. (b) Differential voltage dV/dB for junctions A and D.

2. Direct distinction between giant vortex states and multivortex states in superconducting disks

In Ref. 3 we realized the direct distinction between MVSs and GVSs in mesoscopic disk by using the recently developed MSTJ method. The MSTJ method is based on a classical technique for estimating the superconducting density of states (DOS) from the current-voltage characteristics of a superconductor-insulator-normal metal (SIN) tunnel junction. Since the superconducting DOS depends on the magnetic field and the supercurrent density, the spatial distribution of the DOS provides information on the vortex configuration.

Instead of measuring the DOS everywhere over the sample surface, we just measure the DOS at the symmetrical positions in the sample, e.g. at the periphery for a disk sample. When the DOS at the symmetrical positions takes the same value, the state is likely to be a GVS, and otherwise it is a MVS.

Figure 1(left) shows a scanning electron micrograph of a disk sample for the MSTJ measurement. Four normal-metal (Cu) leads are connected to the periphery of a superconducting Al disk (indicated by the dashed circle) through highly resistive SIN tunnel junctions A, B, C and D. Note that the sample structure (including the junction positions) is symmetric with respect to the central axis, so that the junctions A and D (B and C) are at symmetrical positions. The radius of the disk is 0.75 μm and the disk thickness is 33 nm. The disk is directly connected to an Al drain lead. This structure was fabricated using e-beam lithography followed by double angle evaporation of Al and Cu. Details of the process are described elsewhere [3]. In the measurement, we fixed the current flowing through each junction to a small value, typically 100 pA, and measured simultaneously the voltages between each of the four Cu leads and the drain lead, while sweeping the perpendicular magnetic field at a typical rate of 20 mT/min.

Figure 1(right) shows the change of the voltages at $I = 100$ pA in decreasing magnetic fields. V_a and V_d denote the voltages in symmetric junctions A and D, respectively. To eliminate the influence of small resistance difference between these junctions, dV/dB is also shown in Fig. 1(right). The voltage variation as a function of magnetic field results from two origins: (i) smearing of the energy gap due to pair-breaking by the magnetic field, and (ii) a decrease of the energy gap because of the supercurrent. The former leads to a moderate monotonic decrease in voltage as the strength of the magnetic field increases, so the rapid change in voltage comes from the latter. Especially, each voltage jump corresponds to a transition between different vortex states with a vorticity change of -1. This allows us to identify the vorticity L as shown in the figure. In Figs. 1(right) the difference in V and dV/dB is remarkable for L = 2, 4 - 11, indicating that the state is a MVS for these vorticities. For increasing magnetic fields, the difference in V and dV/dB is relatively large between L = 4 and 6 (not shown), which is also due to the MVS formation. These experimental results are in good agreement with a numerical simulation based on the nonlinear Ginzburg-Landau theory. Detailed analysis is described in Ref. 3.

3. Indirect distinction between giant vortex states and multivortex states

In Ref. 4 we presented an indirect method to distinguish between MVSs and GVSs in mesoscopic disks by studying the temperature dependence of the expulsion field. We found that the expulsion field in a mesoscopic disk with radius $R = 5$ $(T = 0)$ is almost temperature independent when the vortex state is a MVS and that it increases with temperature in case of a GVS. The experimental results obtained using the MSTJ method was in good agreement with the theoretical prediction.

Here, we calculate the *full* phase diagram for a slightly smaller superconducting disk with radius $R = 4$ $(T = 0)$ and we study the behavior of the penetration and expulsion fields as a function of temperature for MVSs and GVSs. To construct the phase diagram, we calculate the free energy of the vortex states in a disk with $R = 4$ $(T = 0)$ for increasing and decreasing magnetic field at various temperature values. Therefore, we solve the two Ginzburg-Landau equations self-consistently, as is described in e.g. Ref. [1]. We assume the following temperature dependences: $(T) = (0)|1\text{-}T/T_{c0}|^{-1/2}$, $(T) = (0)|1\text{-}T/T_{c0}|^{-1/2}$ and $H_{c2}(T) = H_{c2}(0)|1\text{-}T/T_{c0}|$, with T_{c0} the zero field critical temperature.

We calculated the H-T phase diagram for a disk with radius $R = 4$ $(T = 0)$, thickness $d = 0.1$ $(T = 0)$ and Ginzburg-Landau parameter = 0.28. The penetration and expulsion fields as a function of temperature are shown by the symbols in Fig. 2(left). When the last state before the transition is a MVS the transition fields are given by closed symbols, when it is a GVS by open symbols.

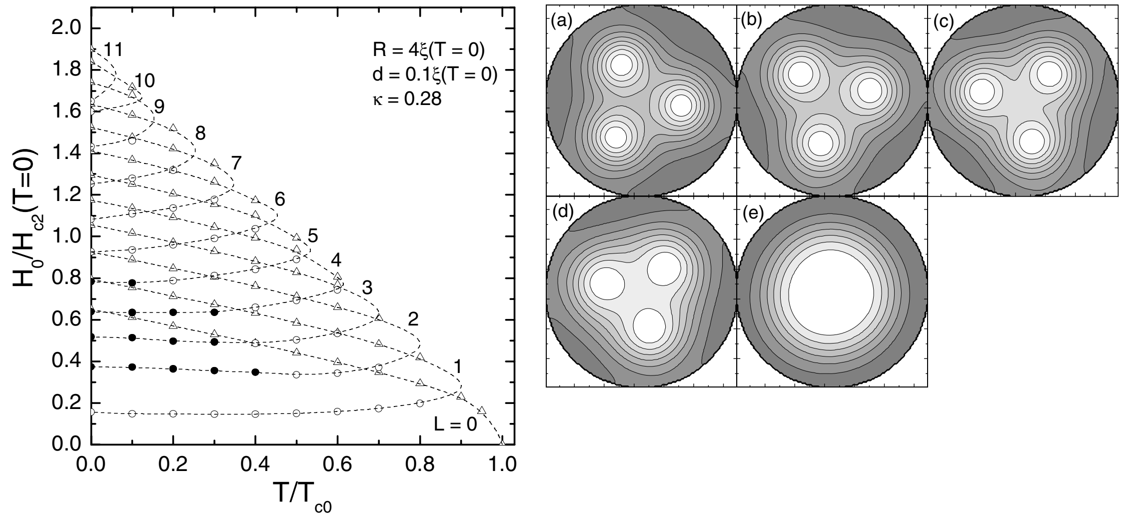

Figure 2. (left) H-T phase diagram. The penetration fields (triangles) and expulsion fields (dots) as a function of temperature. In the case of a GVS (MVS) we use open (closed) symbols. The curves are guidelines for the eye. (right) Contour plots of the Cooper-pair density of the L = 3 state just above the expulsion field, at T/T_{c0} = 0 (a), 0.1 (b), 0.2 (c), 0.3 (d) and 0.4 (e). Dark (light) regions correspond to high (low) Cooper-pair density.

We find that the MVSs only stabilize at low temperatures and in this case the expulsion fields are almost temperature independent, while in the case of GVSs they increase with temperature. Notice further that for fixed vorticity the MVSs always transit into a GVS, which means that the state is always a GVS at the penetration field. This was not the case for a disk with radius $R = 5$ $(T = 0)$ [4]. From Fig. 2(left), it is clear that the stability of the MVSs decreases with increasing temperature. The reason is that the effective size $R/ (T)$ of the disk decreases with increasing temperature, since (T) increases with temperature. This results in the fact that the vortices are pushed more towards the center and the GVS becomes more favorable. To show this more clearly we give in Fig. 2(right) contour plots of the Cooper-pair density for the $L = 3$ state, just before the transition to the $L = 2$ state for different values of temperature. When temperature increases, the three vortices move more towards the center and for $T/T_{c0} = 0.4$ they combine into one giant vortex.

4. Conclusions

In mesoscopic superconducting disks, one can experimentally distinguish between the two types of vortex states, i.e. multivortex states and giant vortex states directly by using the multiple-small-junctions method. When the voltages between each of the Cu leads and the drain lead have the same value, then the state is a giant vortex states. When the voltages are different, the state is a multivortex state.

By studying the temperature dependence of the expulsion fields on can also indirectly distinguish between multivortex states and giant vortex states. We found that the expulsion fields are almost temperature independent when the vortex state is a MVS and increase with temperature in the case of a GVS.

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