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EPR Effect in Magnetic Dependent Dissipation in High Temperature Superconductors

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Electron paramagnetic resonance in ac dissipation was observed due to the Cooper pairs breaking up to their quasiparticle state. This phenomenon is the result of a flux motion on a pinning centers in high temperature superconducting materials. The detection of ac dissipation was performed in a low ac field (15 and 22 MHz) as well as in microwave range. Vortex motion hysteresis loop with magnetic field modulation of 15 Hz was recorded. Besides V-shaped dependence of ac power dissipation $P(B)$, a direct electron paramagnetic resonance signal related to Cooper pairs → quasiparticle fluctuation was observed.

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1. Introduction

In high T_c superconducting materials below critical temperature the absorption of ac field is related to the vortex motion (VM) as a result of Cooper pairs (PC) being broken up to a quasiparticle (QP) state. This, in turn, results in the change of resistance $\Delta R(B)$ proportional to the external magnetic field. Close to $B = 0$, $\Delta R = 0$, because the condensate is not influenced by ac field. With increasing B, close to B_{c2}, the ac field records the appearance of electrons in the QP state above the energy gap. The quasiparticle state manifests itself in losses proportional to the magnetic field B. AC surface impedance in YBCO and other high temperature superconducting (HTS) materials is well described below T_c by Coffey and Clem (CC) [1] vortex motion flow model in the review paper of Golosowsky et al. [2]. This model shows that electric resistance response is very sensitive to the vortex oscillation in a pinning center and to reversible jumping of the vortex between neighboring centers. CC model is related to the case of vortex motion via Lorentz force driven by oscillating current. The potential energy of a pinning center $U(x)$ does not depend on external magnetic field value. However, if in a granular superconductor there are weak links as pinning centers, the potential should include a periodic dependence on B, i.e. $U(x, B)$. This Josephson-like periodicity of the critical current $I_c \sim (\sin \pi \Phi)/\pi \Phi$, close to the zero magnetic field $B = 0$, explains microwave absorption quadratic dependence on magnetic field, $P \sim B^2$. It also allows the explanation of vortex motion hysteresis loop (VMHL) in granular superconductors at low frequency of oscillating magnetic field. In a two-fluid transport mechanism, Bose–Einstein condensate (BEC) characterized by $S = 0$ is disturbed by moving vortex and strong fluctuations of magnetization appear related to the spin of quasiparticle excitation with spin $S = 1/2$. This spin magnetization effect has been directly observed as EPR line at $B = 0.54$ mT at the frequency ac field 15 MHz.

2. Results

AC dissipation in the transport process of charge carriers in high T_c superconductors is due to the vortex motion. There is a toroidal superconducting current J_s around vortex core. The motion flow of vortexes results in the excitation of CP to QP state, therefore in the increase in resistance, is strongly dependent on magnetic field value. The change in resistance related to the CP$\rightarrow$QP fluctuation is the smallest one in the absence of magnetic field. Changing periodically magnetic field B, VMHL related to transport losses $\Delta R(B)$ is observed (Fig. 1a). The viscous process of vortex motion leads to two minima in VMHL. The ac losses hysteresis loop and its shape vs. rate of field B modulation were discussed in the frame of the local temperature of weak Josephson junction system in granular superconductors [3].

On decreasing temperature around T_c there is a resonant absorption from quasiparticles, which like normal electrons exhibit a typical EPR signal shown in Fig. 1a. In Fig. 1b the bottom part of VMHL is better observed, because magnetic field was swept at frequency 50 Hz with halved amplitude compared to that in Fig. 1a. This resonance corresponds to g factor value $g \approx 2$. For oscillating field at frequency 22 MHz around magnetic field value of $B = \pm 0.9$ mT VMHL exhibits typical beat oscillations (Fig. 1b). This points to relatively long spin relaxation.

To separate EPR signal from ac dissipation related to the vortex magnetization, two-coils Bloch probe was applied to detect perpendicular component of magnetization. It turned out that VMHL was still observed because the vortexes are not collinear to the magnetic field but have a meander shape, hence there is a perpendicular magnetization component. At 15 MHz frequency there are distinct EPR satellites (shown in Fig. 2a) at $B = \pm 0.54$ mT around zero field on V-shaped vortex motion hysteresis loop. This has been proved by observation of EPR for DPPH standard sample presented in Fig. 2b.

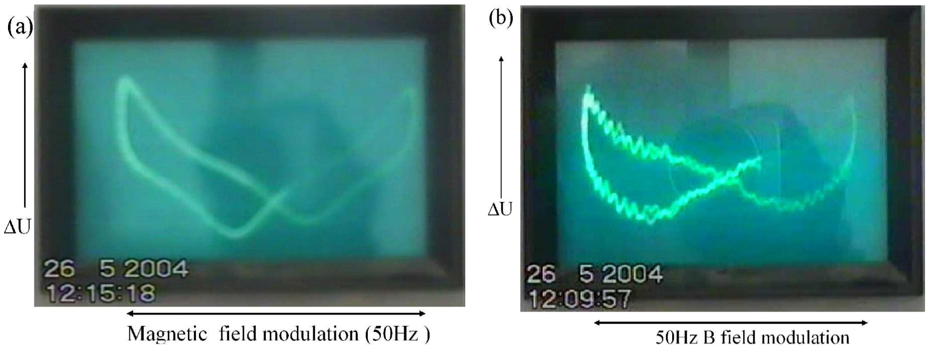

Fig. 1. (a) VMHL in YBCO ceramic sample at $T = 77$ K at 22 MHz frequency; (b) EPR signal at $B \approx 0.9$ mT close to $T_{\rm c} = 90$ K.

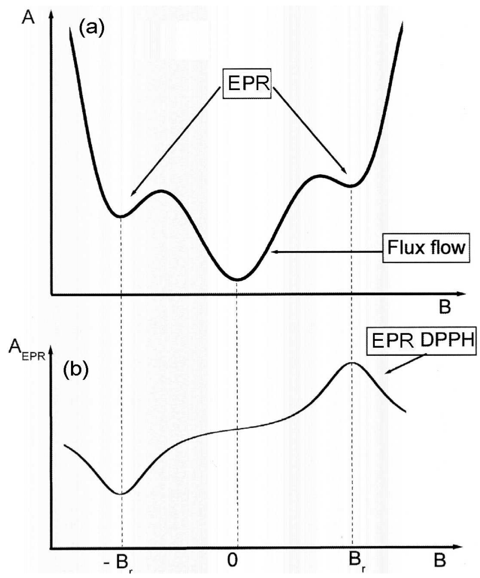

Fig. 2. VMHL for ceramic YBCO sample in the Bloch-type probe at 15 MHz. (a) EPR satellites are separated by ± 0.54 mT; (b) EPR of DPPH sample.

After EPR observation of QP state, analysis of transport measurements published by Silva et al. [4] showed that EPR of quasiparticles can be responsible for an anomaly in surface resistance (Fig. 3a). In a microwave range (21 GHz) vortex motion resistance for YBCO has a distinct anomaly corresponding to resonant absorption EPR at $B = 0.66$ T. From experimental real part of resistance of [4] ($\Delta\rho$ in Fig. 3a) the monotonic curve was subtracted; the resulting $\delta\rho$ anomaly is presented in Fig. 3b. This anomaly shows a distinct maximum. The maximum of this absorption corresponds to the Cu^{2+} paramagnetic center in $d_{x^2-y^2}$ orbital state of copper with $g = 2.27$. This means that quasiparticles, those being local-

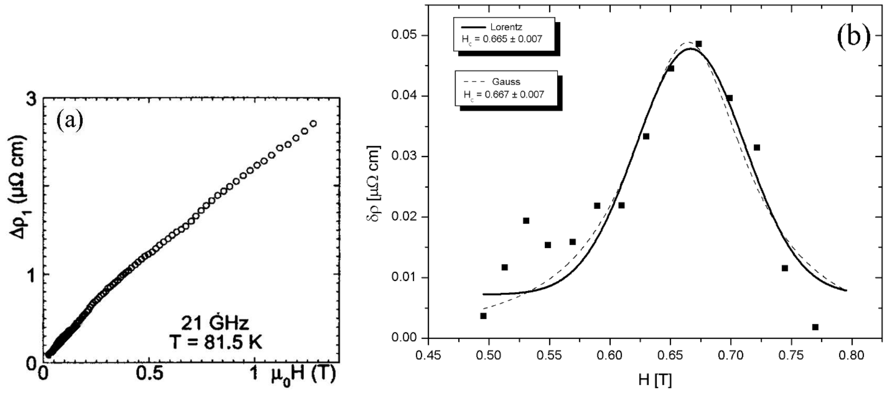

Fig. 3. (a) Vortex motion resistance according to data of [4]; (b) EPR anomaly ($\delta\rho$) with the maximum at $B = 0.66$ T extracted after the computer analysis from $\Delta\rho$ presented in (a).

ized observed by EPR, are d electrons. This implies that pairing in YBCO has a component with d symmetry.

Previously observed EPR anomaly in magnetic susceptibility also points to the fact that conducting electrons in alkali metal-doped fullerene C_{60} quasiparticles have a p symmetry related to non-paired spin confined on C_{60}^{1-} ions [5].

3. Conclusions

1. This makes the first direct observation of EPR close to phase transition T_c showing that Cooper pairs with $S = 0$ undergo the fluctuation to its quasiparticle state with $S = 1/2$.
2. g-Factor shows that the observed spin state is a localized state d, which contributes to the conducting band.
3. Low field EPR and paramagnetic fluctuation can be applied to study interactions between local pairs (boson liquid) and quasiparticles (quasi Fermi liquid).

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