Flux quantum tunneling effect and its influence on the experimental critical current density*

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Abstract By using magnetic sweeping method, the temperature and magnetic field dependencies of the experimental current density and the normalized relaxation rate have been obtained. The true critical current density corresponding to the zero activation energy has been carried out based on the collective-pinning and the thermally-activated flux motion models, and therefore the influences of the quantum tunneling effect and the thermal activation effect on the experimental critical current density are distinguished. It is found that, with temperature lower than 10 K, the relaxation rate will not drop to zero when T approaches zero K because of the occurrence of the flux quantum tunneling. This additional flux motion further reduces the experimental critical current density j making it saturated with lowering temperature.

Keywords: flux quantum tunneling effect, thermally-activated flux motion, collective-pinning, critical current density.

One of the difficulties concerning the application of high temperature superconductors is the energy dissipation. According to the thermally-activated-flux-motion model (hereafter abbreviated as TAFM), when the current density j is larger then $0.1-0.2\,j_c$, the reverse hopping becomes negligible. Thus the thermal activation energy can be written as[1]

$$U(j,\ T,\ B)=k_BT\cdot\ln(v_0B/E(j,\ T,\ B)), \tag{1}$$

where v_0 is the maximum velocity of flux motion, and E the electric field induced by the flux motion. In the field sweeping process, according to Faraday's law, E is proportional to $\mathrm{d}B/\mathrm{d}t$. At a certain temperature, the derivation of the double logarithmic curve $\ln E$ versus $\ln j$ is

$$\mathrm{d}\ln j/\mathrm{d}\ln(\mathrm{d}B/\mathrm{d}t)=-k_BT(\mathrm{d}U(j,\ T,\ B)/\mathrm{d}\ln j), \tag{2}$$

where $\mathrm{d}B/\mathrm{d}t$ is the field sweeping rate, and the term on the left-hand side is the so-called dynamical relaxation rate. The commonly used method for investigating the flux motion is the magnetic relaxation[2–4], which is to measure the relaxation of magnetization with time at certain temperatures and fields, with the relaxation rate s defined as $s=-\mathrm{d}\ln M/\mathrm{d}\ln t$. Since M is proportional to j, $s=-\mathrm{d}\ln j/\mathrm{d}\ln t$. The method mentioned above

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is very efficient for investigating the flux motion of single crystals or the bulk samples, but in the case of thin film it becomes less efficient because of the occurrence of overshoot effect during the initial relaxation process. Jirsa *et al.*[5] and Schnack *et al.*[6] indicated that this difficulty can be avoided by using the field sweeping method. The relaxation rate can be equivalently determined to be $Q=\mathrm{d}\ln j/\mathrm{d}\ln(\mathrm{d}B/\mathrm{d}t)$. In a forthcoming paper we will show that the equivalence of the sweeping method and the transport measurement will enable us to obtain the relaxation rate in a wide temperature region.

From the above discussion, we know that the term on the left-hand side of eq. (2) is the magnetic relaxation rate. Since $\mathrm{d}U/\mathrm{d}\ln j$ is not equal to 0, Q should be 0 at $T=0$ K, indicating that according to the TAFM model, the flux motion will stop at $T=0$ K. However, many experiments have shown that Q or S does not drop to 0 when $T=0$ K[7—9], which is attributed to the flux quantum tunneling effect[10, 11]. At a certain temperature, the thermal activation and the quantum tunneling will influence the flux motion together. Up to now there have been no theoretical models to distinguish these two effects and their influences on the critical current density. In this paper, we will report the flux quantum tunneling effect observed by means of the field sweeping in $YBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_4O_8$ thin films. Using the collective flux pinning model, the influence of TAFM on the experimental critical current density was successfully separated from the flux quantum tunneling effect.

1 Experimental

A highly sensitive magnetic torque meter (10^{-6}—10^{-7}emu)[12, 13] was used to measure the magnetic torque moment of the sample. The temperature was measured by a calibrated RuO_2 semiconductor thermometer and a standard Pt resistance thermometer, and controlled by a commercial automatic temperature controller. The field was 45° to the *c*-axis of the film. Two pieces of high quality $YBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_4O_8$ thin films made by molecular beam epitaxy technique on $SrTiO_3$ substrates were used as the samples. Their transition temperatures were atout $T_{c0}=90.8$ K(Y123) and $T_{c0}=78.5$ K(Y124). The transition width of both samples was about 0.5 K. X-ray diffraction (XRD) showed that only (00$\underline{l}$) peaks were observable and the full widths at the half height (FWHH) of (005) peak was about 0.3° for Y123 and 0.5° for Y124, which indicated that the films had very good crystallinity. The thicknesses were 180 nm (Y123) and 100 nm (Y124), respectively.

2 Results

The temperature dependence of the relaxation rate Q for Y123 and Y124 are presented in fig. 1(a) and fig. 1(b), respectively. The Q value was determined in the following ways: first, at a certain temperature, the magnetic field was sweeping up and down at a certain rate near a certain field; then the experimental critical current density corresponding to a certain

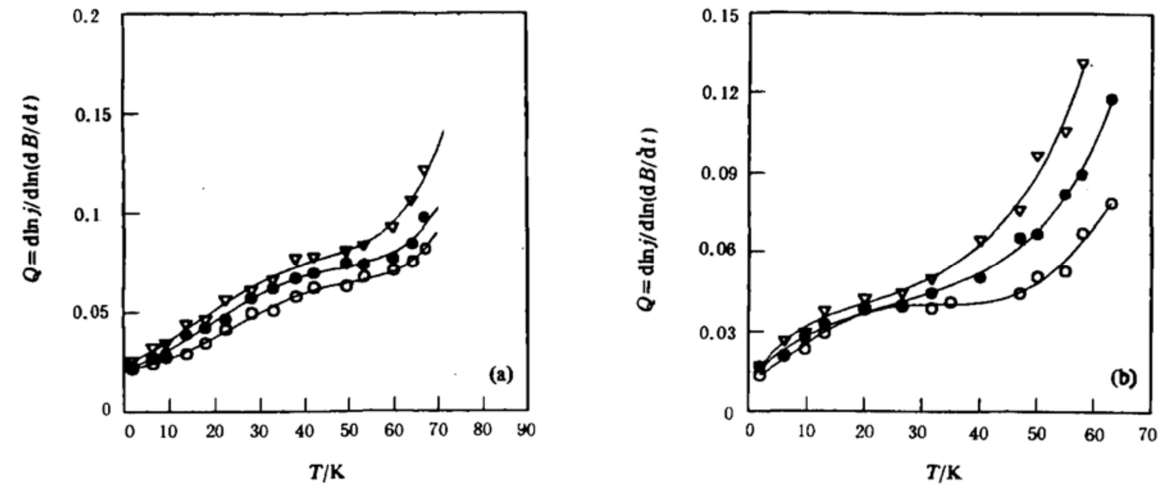

Fig. 1. Temperature dependence of the relaxation rate for (a) $YBa_2Cu_3O_{7-\delta}$ and (b) $YBa_2Cu_4O_8$ thin films. ▽, $B=2\,T$; ●; $B=1\,T$; ○, $B=0.5\,T$.

field and sweeping rate was determined from the irreversible width of the magnetization. Repeating the above process at a new sweeping rate, we can obtain the $j(B,\ dB/dt)$ curves. The Q value was then determined through $Q=d\ln j/d\ln(dB/dt)$. All the data used in this paper were taken at a sweeping rate of $4\times 10^{-2}\,T/s$. From fig. 1 it is easy to find that Q value cannot be extrapolated to 0 K by lowering the temperature. The experimental critical current densities are plotted in fig. 2(a) and fig. 2(b) for Y123 and Y124, respectively. The sample was patterned into a small ring with an inner diameter of 7 mm and an outer diameter of 8 mm. With $dB/dt=4\times 10^{-2}\,T/s$, the electric field induced in the ring is $E_c=7.5\times 10^{-5}\,V/m$. In fig. 2 typical features can be observed: (i) with decreasing temperature, j increases quickly in the intermediate temperature region, but a saturation can be easily observed when T is lower than a certain value; (ii) the Q shows a plateau in the intermediate region. In the next section, we will see that the former case is due to the

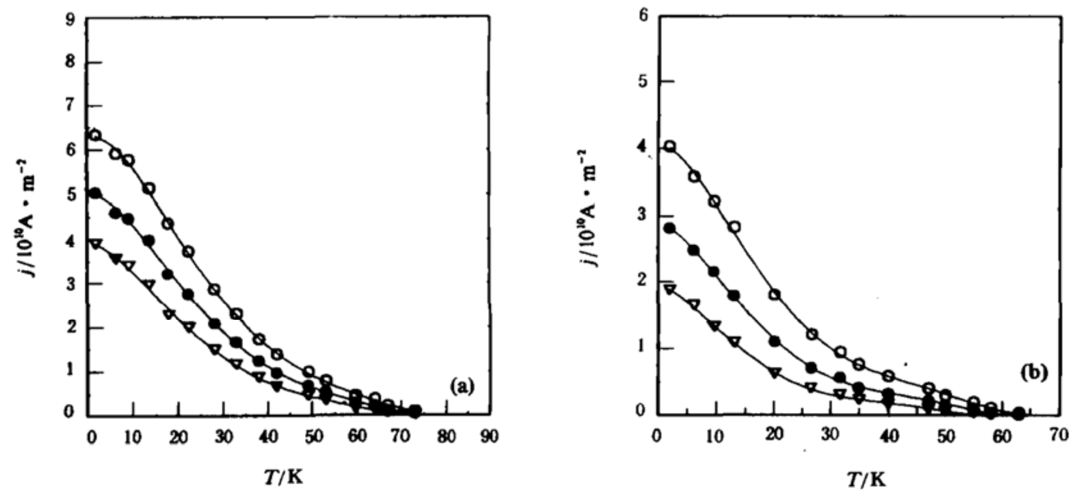

Fig. 2. Temperature dependence of the experimental critical current density for (a) $YBa_2Cu_3O_{7-\delta}$ and (b) $YBa_2Cu_4O_8$ thin films. The voltage criterion is $7.5\times 10^{-5}\,V/m$. ○, $B=0.5\,T$; ●, $B=1.0\,T$; ▽, $B=2\,T$.

flux quantum tunneling effect, while the latter is due to the thermally activated flux creep of collectively pinned flux bundles.

3 Discussion

To distinguish the TAFM and the flux quantum tunneling effect, one of the efficient ways is to determine the influence of TAFM on the experimental critical current density. In the case of high temperature superconductor, it is supposed that the flux line (or bundle) is pinned by many weak pinning centers collectively. According to the collective pinning model the thermal activation energy is[14, 15]

$$U=[U_c(T,\ B)/\mu(j)]\cdot[(j_c(T,\ B)/j)^{\mu(j)}-1], \tag{3}$$

where U_c is the characteristic pinning potential, j_c is the true critical current density corresponding to $U=0$ and μ is an exponent for collectively pinned single vortex, it is predicted that $1/7<\mu<1.5$[14]; for large flux bundles when the current density is small, μ is expected to be 0.5[16].

From eqs. (1) and (3) as well as $E=(R/2)\cdot(\mathrm{d}B/\mathrm{d}t)$, we have

$$j(T,\ B,\ \mathrm{d}B/\mathrm{d}t)=j_c(T,\ B)/[1+\mu k_B T\cdot\ln(2v_0B/R(\mathrm{d}B/\mathrm{d}t))/U_c]^{1/\mu}. \tag{4}$$

At a certain temperature and magnetic field, differentiating both sides of eq. (4) with respect to $\ln(\mathrm{d}B/\mathrm{d}t)$ yields

$$Q=Q_0/[1+(cQ_0-\ln(j_c/j))\cdot\mathrm{d}\ln\mu(j)/\mathrm{d}\ln j], \tag{5}$$

where

$$Q_0=k_BT/[U_c+\mu(j)ck_BT] \tag{6}$$

and

$$c=\ln[2v_0B/R(\mathrm{d}B/\mathrm{d}t)]. \tag{7}$$

Since c is related to the magnetic field and the temperature through a logarithmic function, it can be treated as a constant. In addition, from eq. (5) we know that, if μ is a weak current-dependent function, then $\mathrm{d}\ln\mu(j)/\mathrm{d}\ln j\approx 0$; therefore we have $Q\approx Q_0$. Actually, we will see that this condition can be satisfied when $j>0.1\ j_c$. Thus eq. (5) becomes

$$T/Q=U_c/k_B+\mu cT_0. \tag{8}$$

In eq. (8), if we know two of the three parameters μ, c and U_c, we can determine the third one. In the following we will see that c value can be determined in a separate way. From eqs. (4) and (8), we obtain

$$\mathrm{d}\ln j/\mathrm{d}\ln T=\mathrm{d}\ln j_c/\mathrm{d}\ln T-Qc. \tag{9}$$

We know that j_c is related to temperature through H_c, ξ and λ, which are weak temperature-dependent functions in low temperature regions; therefore we have

$$c = -(T/Q)\cdot(\mathrm{d}\ln j/\mathrm{d}\ln T)|_{T\to 0}. \tag{10}$$

The temperature dependences of T/Q and $\ln j$ are plotted in figs. 3(a) and 3(b). It is clear that in a large temperature region, T/Q and $\ln j$ depend on temperature T linearly, which is helpful for determining the c value. But let it be noted that at about $T=10\,\mathrm{K}$, T/Q and $\ln j$ start to deviate from the linear part in the intermediate temperature region, because the flux quantum tunneling effect will prevail over the thermal activation effect; therefore we cannot use the data at $T\leqslant 10\,\mathrm{K}$ to determine c value. As soon as c value is determined, from eq. (8) we can determine μ value and the characteristic pinning potential U_c by calculating the slope of T/Q versus T and its intercept with the vertical axis. From fig. 3(a) we see that T/Q depends on T linearly, which indicates that the μ value is almost a constant. This is the prerequisite of using eq. (8). Since U_c is related to temperature through $(1+t)^{\alpha}(1-t)^{\beta}$, at temperatures $T<0.5\,T_c$, it will change slowly[17]. Thus we can treat it as a constant in the low temperature region. In table 1 are listed the μ, U_c and c values determined by this method.

Table 1 U_c, c and μ values obtained with the collective-pinning model

B/T		0.5	1	2
Y123	$U_c(T=0\,\mathrm{K})$	358	280	250
	μ	0.54	0.59	0.46
	c	15	13.5	13.4
Y124	$U_c(T=0\,\mathrm{K})$	235	200	160
	μ	1.03	1.00	0.99
	c	17	12	15.5

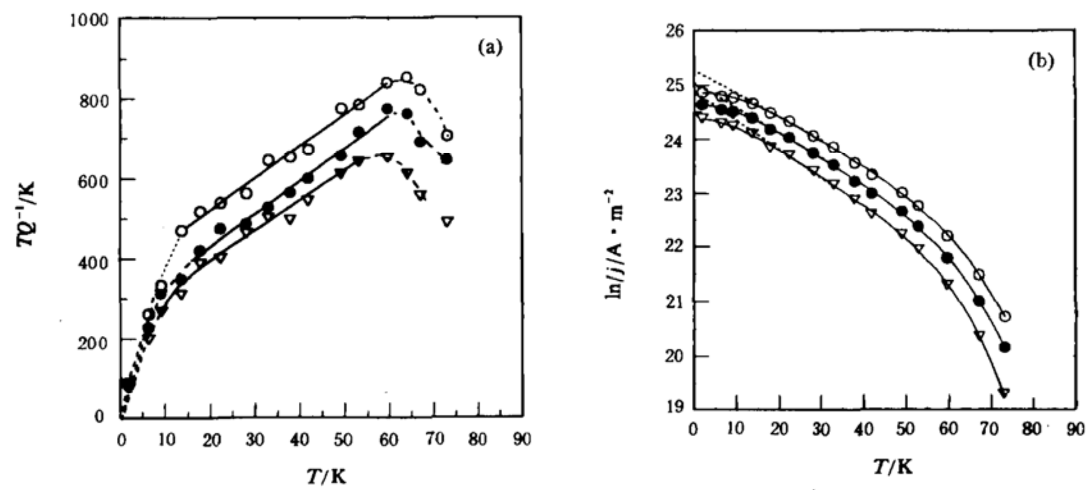

Fig. 3. (a) Correlation between T/Q and T for the $YBa_2Cu_3O_{7-\delta}$ thin film. The straight line in the low temperature region shows the predictions of the collective-pinning model. (b) Temperature dependence of the logarithm of the experimental critical current density for the $YBa_2Cu_3O_{7-\delta}$ thin film. It is clear that in the large temperature region, the data fall onto a straight line. ○, $B=0.5\,\mathrm{T}$; ●, $B=1\,\mathrm{T}$; ▽, $B=2\,\mathrm{T}$.

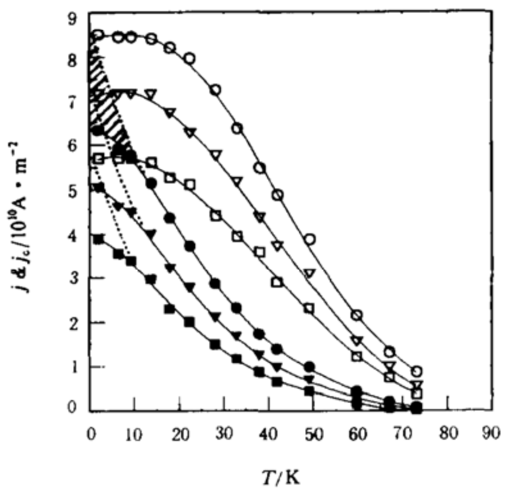

Fig. 4. Comparison between the experimental critical current density (●) and the true critical current density (○). The shade area shows a further decrease in the experimental critical current density due to the flux quantum tunneling effect. ○, $B_\cdot$ =0.5 T; ▽, B=1 T; □, B=2 T.

As soon as the three parameters μ, U_c and c are determined, with the experimental measurable parameters T, Q and J, we can determine the true critical current density using eq. (4). In fig. 4 are presented the temperature dependencies of the experimental and true critical current densities. Because of the existence of the flux quantum tunneling effect in low temperature region, we can never measure the decrease in the experimental critical current density caused by the TAFM. Therefore, we are not able to know the true critical current density at $T=0\,\text{K}$. However, as is known, $\mathrm{d}j_c/\mathrm{d}T|_{T>0}=0$, we can set $j_c(0\,\text{K})=j_c(13.6\,\text{K})$. In fig. 4, the dashed line shows the current density due to the conventional flux creep, which was determined by using the TAFM model in combination with the μ, U_c and c values in table 1. It is clear that the experimental data at $T\geqslant 13.6\,\text{K}$ agree well with the calculated data at $T\leqslant 13.6\,\text{K}$. This may serve as collateral evidence of the veracities of our analysis method.

In the case of high field, this method will be invalid, since the mean squared root of the displacement is mainly determined by the quantum tunneling effect[11]. In a limited temperature region, Blatter *et al.*[10] predicted that the relaxation rate Q will increase with the temperature as $Q(T=0)/(1-AT^2)$. But, up to now, no experiment evidence has been found, which is mainly due to the coexistence of TAFM. This will be discussed in another paper.

4 Conclusions

With the collective pinning model, we obtained the temperature dependence of the true critical current density and separated the influences of the flux quantum tunneling effect and the thermally activated flux motion on the experimental current density. It is found that at temperature lower than 10 K, the flux quantum tunneling effect will prevail over the thermal activation effect, which leads to nonzero relaxation rate and a further depressing of the experimental critical current density.

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