# The 'irreversibility line' of $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$



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# The 'irreversibility line' of $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$

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**Abstract.** The magnetization 'irreversibility line' of $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$ was studied. The results showed that, characteristically, it is similar to that of Bi superconducting compounds, although the structure of this superconductor is close to that of 1:2:3 yttrium superconductors.

## 1. Introduction

Since high-$T_c$ superconductors were discovered, the magnetic properties have been intensively investigated. Müller *et al* [1] first reported that the 'irreversibility line' of $La_{2-x}Ba_xCuO_{4-y}$ follows a simple power law: $H^*(T) = H_0(1 - T/T_c)^{3/2}$ where $H^*(T)$ is the tangent point of the zero-field-cooled (ZFC) curve $M_Z(T)$ and the field-cooled (FC) curve $M_F(T)$ at magnetic $H^*$. Müller *et al* considered it to be the Almeida–Thouless line for superconducting glasses. The line separates the region in the $(H, T)$ plane in which the magnetization $M$ is reversible from the region in which $M$ depends on the previous path in the $(H, T)$ plane. Yeshurun and Malozemoff [2] have shown that a similar line exists in the YBCO single crystal and can be explained by flux creep.

Dai *et al* [3] and de Rango *et al* [4] have studied the irreversibility lines of Bi compounds and found that their characteristics are very different from that of Y superconductors. At high fields, the irreversibility points $T^*(H)$ are depressed to a temperature much below $T_c$ and are closed to the 'melting temperature of the flux lattice' of Gammel *et al* [5]. At low fields and near $T_c$, they follow $H(T) = H_0(1 - T/T_c)^{3/2}$. de Rango *et al* have found that at high fields and low temperatures the 'irreversibility line' of the Bi 2:2:2:3 superconductor can be fitted to an exponential form $H^* \sim \exp(-T/T_0)$. They argued that $H^*$ is the breakdown field for the proximity effect at the 'normal block' SrO–BiO–BiO–SrO between 'the superconducting blocks' of three $CuO_2$ layers. The existence of the proximity effect is related to the high anisotropy of the structure. In the Bi 2:2:2:3 compound, the separation between the $CuO_2$ layer blocks is about 12.16 Å and the SrO–BiO–BiO–SrO block is more weakly superconductive than the Cu–O chain in YBCO as indicated by the larger anisotropy of superconductivity in the former compound.

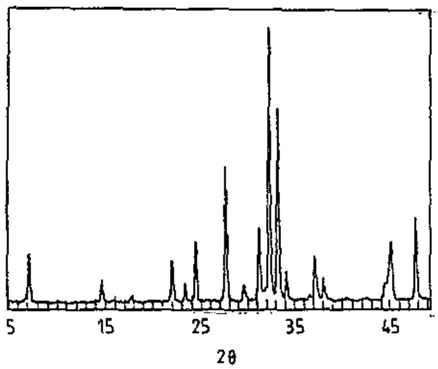


**Figure 1.** XRD spectra for $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$.

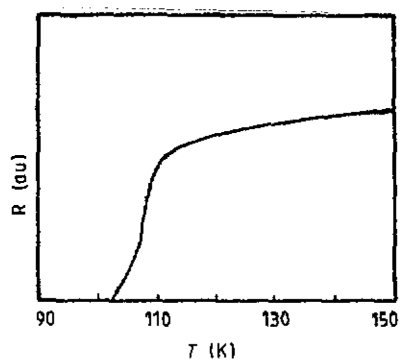


**Figure 2.** The temperature dependence of the resistance for $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$.

According to [2, 4], the 'irreversibility line' originates from the large flux creep in high-$T_c$ superconductors and relates to the low thermal activation energy caused by the high anisotropy and the small coherence length.

The structure of the Tl 1:2:1:2 superconductor is very similar to that of YBCO. The small difference between them is that the Cu–O chain in YBCO is replaced by the Tl–O layer. The separations between the superconducting $CuO_2$ layer blocks in these superconductors are almost the same. Therefore there is the same anisotropy in the structure for these two compounds. The investigation of the 'irreversibility line' of the Tl 1:2:1:2 compound should be very interesting. In this paper we shall give the results on $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$ samples. It will also be reported that above $T^*$ the reversible magnetization obeys the well known expressions for an Abrikosov lattice of interacting vortices as obtained by de Rango *et al* for the Bi 2:2:2:3 compound.

## 2. Experiment

The sample in this work is $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$. It was prepared by first weighing appropriate amounts of PbO, $SrO_2$, CaO, $Y_2O_3$ and CuO powders in stoichiometric proportions of $Pb_{0.4}Sn_{0.2}Sr_2Ca_{0.8}Y_{0.2}Cu_2O_y$. After grinding, the well mixed oxides were calcined at 920 °C in air for 12 h. The final specimen was prepared by mixing with an appropriate amount of $Tl_2O_3$. The mixture was ground and pressed into a pellet. The sample was sintered several times. Each time, additional $Tl_2O_3$ was added to compensate for the volatilization of Tl at high temperatures. The sintering temperature is about 920–940 °C. The total time for sintering is about 3 h. The sample was slowly cooled to room temperature (100 °C $h^{-1}$). The x-ray diffraction pattern shows a single phase (figure 1). The zero-resistance temperature for the superconducting transition is about 103 K (figure 2). The ZFC and FC magnetizations were measured with a moving-sample magnetometer.

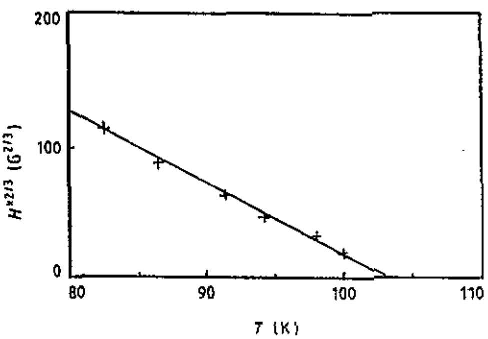


**Figure 3.** The low-field range of the irreversibility line for $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$.

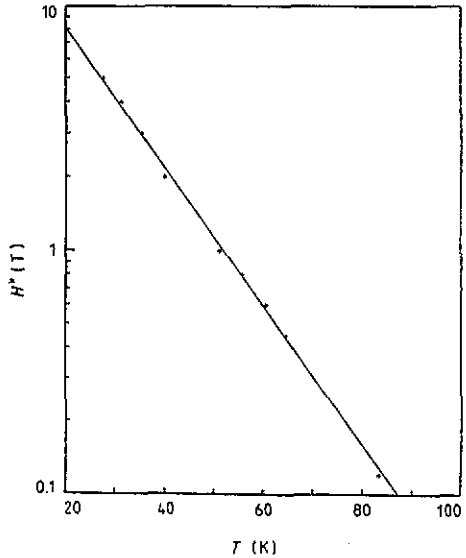


**Figure 4.** The high-field range of the irreversibility line for $(Tl_{0.4}Pb_{0.4}Sn_{0.2})Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_y$.

## 3. Results and discussion

From the ZFC and FC magnetizations we have obtained the irreversibility points $T^*(H)$. In figure 3, the low-field part of the irreversibility line is shown and it can be fitted to the universal behaviour

$$H^* = A(1 - T/T_c)^{3/2} \tag{1}$$

where $H^*$ is in oersteds. Here the constant $A$ is about 13300.

At high fields the irreversibility points $T^*$ are depressed to temperatures much lower than $T_c$. According to the opinion of de Rango *et al*, the 'irreversibility line' corresponds to the breakdown field of the proximity effect in the 'normal' block between the superconducting $CuO_2$ layers.

In the proximity effect [6] and in the 'clean' limit, the breakdown field varies exponentially with temperature following the relation

$$H = H_0 \exp(-d_N 2\pi\kappa_B T/hV_N) \tag{2}$$

where $d_N$ is the thickness of the normal block and $V_N$ is the Fermi velocity in the 'normal' material. Figure 4 shows the high-field part of the 'irreversibility line' in this compound. It can be fitted to an exponential form of

$$H^* = 300000 \exp(-T/T_0) \tag{3}$$

where $T_0 \simeq 15.4$ K. This value is slightly larger than the value of 13.3 K obtained by de Rango *et al* for the Bi 2:2:2:3 compound. In the Bi 2:2:2:3 compound the thickness of the 'normal' block SrO–BiO–BiO–SrO is about 12.16 Å. In the sample used in our work, the single Tl–O layer substitutes for the double Bi–O layers. The 'normal' block is SrO–Tl(Pb)O–SrO, the thickness of which is about 8–9 Å and is obviously smaller than that

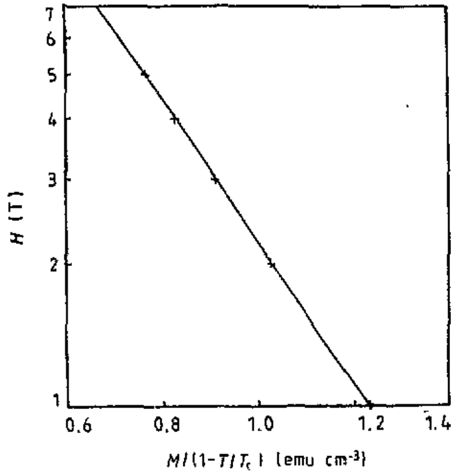


**Figure 5.** The linear dependence of $M/(1-T/T_c)$ versus ln $H$ in the reversible magnetization range above the irreversibility point $T^*(H)$ for the sample.

for Bi superconductors. From equations (2) and (3), $T_0$ is inversely proportional to the thickness of the 'normal' block. If these two compounds have the same $V_N$, it is reasonable to find that $T_0$ for the single Tl layer superconductor is larger than that of the Bi compound.

de Rango *et al* [4] pointed out that above the 'irreversibility point' $T^*(H)$ the magnetization depends linearly on temperature and obeys the well known law for an Abrikosov lattice of interacting vortices in ideal type II superconductors. In the region $H_{c1} \ll H \ll H_{c2}$ [7],

$$4\pi M = (\phi_0/8\pi\lambda^2)[\ln(H - H_{c1}) - \ln(\phi_0/4\pi\xi^2)] \tag{4}$$

where $\ln(H - H_{c1})$ can be replaced by ln $H$ for $H$ far from $H_{c1}$. If $\lambda = \lambda_0\sqrt{1 - T/T_c}$ and because $(\ln \phi_0)/4\pi\xi^2$ is slowly varying with temperature, equation (4) can be expressed as

$$M = A(1 - T/T_c)(\ln H - B) \tag{5}$$

where $A$ and $B$ are independent of $H$ and $T$ but differ with different materials. Our experimental result satisfies (5). In figure 5 the linear dependence of $M/(1 - T/T_c)$ versus ln $H$ is shown. From the data we have

$$M = 1.47(1 - T/T_c)(\ln H - 13.46) \tag{6}$$

where the unit of $M$ is electromagnetic units per cubic centimetre and $H$ is in oersteds. From (4)–(6) the penetration depth and the coherent length can be calculated. We found that $\lambda_0 \simeq 208$ nm and $\xi \simeq 1.53$ nm. These are reasonable values. Because $\kappa = \lambda/\xi$ and $H_{c2} = \phi_0/2\pi\xi^2$, we can estimate that $\kappa \simeq 136$ and $H_{c2} \simeq 140$ T. However, we want to note that the second term in the square brackets in equation (4) is dependent on temperature although the dependence is very small. Therefore the $\xi$-value obtained from equation (6) is an average value in the temperature range of our experiment, and not $\xi_0$. The true values of $\kappa$ and $H_{c2}$ should be somewhat higher than the values given above.

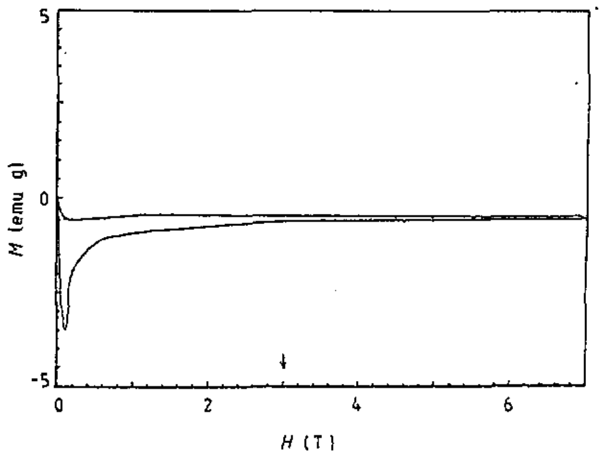


**Figure 6.** The hysteresis loop $M(H)$ of the sample at a temperature of 35 K. The arrow indicates the irreversibility point $H^*(T)$.

It is interesting that the 'irreversibility line' for the single Tl–O layer superconductor shows a very similar behaviour to that for Bi compounds, although the structure of the former material is similar to that of the Y 1:2:3 superconductors. The main difference between the structure of a single Tl–O layer superconductor and the Y 1:2:3 materials is that the Cu–O chains in the Y 1:2:3 superconductor are replaced by the single Tl–O layer. The effect of this replacement on the magnetic properties reflects a large difference between the single Tl–O layer and the Cu–O chain. From the viewpoint of the proximity effect in [4], this phenomenon would show that the single Tl–O layer exhibits a weaker superconductivity than the Cu–O chains and the breakdown field is lower. Here we note one of the various possible alternative opinions. Han *et al* [8] considered that, because there are many twins in the Y superconductors in the plane of the Cu–O chain, the Cu–O chains are broken off at the twin boundary, and many O vacancies can be produced there. As a carrier reservoir of the Cu–O chain plane the compositions of the region near the twin boundary are approximately insulator compositions. This region can be considered to provide pinning centres for flux lines. The single Tl layer superconductor, however, is tetragonal and there is no twin in this material. From this point of view, the absence of a twin can cause weaker intrinsic pinning and consequently also a lower breakdown field. However, the origin of the difference between the single Tl layer superconductor and Y compounds remains to be further investigated.

Finally we note that in the measurement of ZFC and FC magnetizations above the 'irreversibility point' $T^*(H)$ the magnetization $M(T)$ is reversible, but the hysteresis loop $M(H)$ shows that this reversibility is not exact; even when the field $H$ is higher than the irreversibility point $H^*(T)$, the magnetization exhibits a small irreversibility. Figure 6 shows this situation. In figure 6, we can see that above $H^*(T)$ while there is a small irreversibility the magnetization is negative also. It cannot be explained by Bean's simple model. The hysteresis reported in figure 6 seems in contradiction to the discussion of equations (4)–(6). More investigation is needed. It seems that this small irreversibility could be produced by a few local pinning areas.

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