Superconductivity above 250 K 
in Tl$_{1.8}$Ba$_{2.0}$Ca$_{2.6}$Cu$_{3.0}$O$_{10+\delta}$ at high pressure

C. Y. Han$^1$, W. Lin$^2$, Y. S. Wu$^2$, B. Yin$^1$, and D. S. Tang$^1$

$^1$ State Key Laboratory of Magnetism, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China
$^2$ Changsha Research Institute of Mining and Metallurgy, Changsha, Hunan 410012, China

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The pressure dependence of the superconducting transition temperature $T_c$ (onset) of Tl$_{1.8}$Ba$_{2.0}$Ca$_{2.6}$Cu$_{3.0}$O$_{10+\delta}$ (Tl-2223) has been measured under quasi-hydrostatic pressure (QHP) up to 5.0 GPa. The $T_c$ increases with increasing pressure at a relatively high rate and reaches a maximum at 255.4 K and pressure of about 4.3 GPa. This is the highest $T_c$ yet observed for any high-$T_c$ superconductor. The total change in $T_c$ from ambient condition ($T_c = 129$ K) to the high pressure applied can be greater than 126 K. The $T_c$ above 290 K was replicated several times in our experiments. The site of the maximum of $T_c$ and the value of $dT_c/dP = 1.7$ K/GPa (at $P = 0$) agree with previous results obtained by D. Tristan Jover et al. [1] and J. G. Lin et al. [2], respectively.

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1. Introduction

High pressure has played an important role in identification of new materials and mechanisms in high-temperature superconductivity [1–3]. The pressure dependence of the critical temperature of high-temperature superconductors has been studied extensively. For example, L. Gao et al. [3] obtained a much higher value of $T_c$ (164 K) at a pressure of up to 31 GPa in the high-$T_c$ superconductor HgBa$_2$Ca$_2$Cu$_2$O$_{8+\delta}$ (1223). D. D. Berkley et al. [4] observed a maximum $T_c$ of 131.8 K at 7.4 GPa in single crystals of Tl$_2$Ba$_2$Ca$_2$Cu$_3$O$_{10+\delta}$. Tristan Jover et al. [1] obtained the superconducting transition temperature in Tl$_2$Ba$_2$Ca$_2$Cu$_3$O$_{10+\delta}$, which increased from 128.5 K to 133 K with increasing pressure from 0 to 13 GPa. The maximum value of $T_c$ (onset) in this compound was found at pressure of about 4.0 GPa. A systematic study of the pressure effects on the superconducting transition temperatures of Tl-based family has been made by J. G. Lin et al. [2], who obtained $dT_c/dP = 2.5$ K/GPa for Tl-2223 samples at a pressure of only up to 2 GPa.

From their plot of $T_c$ vs $P$ for a Tl-based compound system, it seems that for Tl-2223 and Tl-2122 compounds the $T_c$ may be further enhanced. In view of these circumstances and based upon our previous experience in high-pressure experiments, we have carried out some experiments on Tl-2223 compounds.

Here we report our investigation on the superconductivity of Tl$_{1.8}$Ba$_{2.0}$Ca$_{2.6}$Cu$_{3.0}$O$_{10+\delta}$ compound under high pressures up to 5.0 GPa. We found that $T_c$ changes rapidly with applied high pressures, especially in the range of pressures from 3.0 to 4.0 GPa. The $T_c(P)$ is observed to increase from 129 K at atmospheric pressure to 255.4 K at 4.3 GPa.

2. Experimental

The samples were prepared by using the ordinary solid reaction technique. After the powders of Tl$_2$O$_3$, CaO, BaO, and CuO had been thoroughly mixed and ground, they were pressed into pellets with a diameter of ~12 mm and thickness of ~2 mm, and then sintered at 890 °C for 5 h in flowing oxygen gas. The samples prepared in this way were then put into quartz cells, which were evacuated to $10^{-4}$ Torr, sealed, heat treated at 750 °C for 250 h, and finally air-quenched to room temperature [5]. Samples (30×50×300 μm$^3$) used for measurements under quasi-hydrostatic pressure (QHP) up to 5.0 GPa were cut from the above pellet.
3. Results and discussion

The X-ray powder diffraction patterns for an as-prepared sample Tl$_{1.8}$Ba$_{2.0}$Ca$_{2.6}$Cu$_{3.0}$O$_{10+\delta}$ measured with a RAX-10 X-ray diffractometer (Fig. 1) show a nearly perfect single phase of Tl-2223 with a tetragonal unit cell with parameters $a = 3.85$ Å and $c = 35.70$ Å.

The dc magnetization was measured using a SQUID magnetometer (quantum design). The ZFC magnetization as a function of temperature for the Tl$_{1.8}$Ba$_{2.0}$Ca$_{2.6}$Cu$_{3.0}$O$_{10+\delta}$ sample in a field of $H = 5$ Oe and at ambient pressure shows a sharp single-phase superconducting transition at 129 K and anisotropic factor of 19% (Fig. 2).

In order to determine the uncertainty of the temperature measurements, the system was put into a liquid LN2, of 77.4 K and the ice water of 273.15 K, respectively. Under this condition the temperature uncertainties are shown in Table 1.

<table>
<thead>
<tr>
<th>Sample temperature</th>
<th>$P = 0$ GPa</th>
<th>$\Delta T(K)$</th>
<th>$P = 3.5$ GPa</th>
<th>$\Delta T(K)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>77.4 K</td>
<td>77.44 K</td>
<td>0.04</td>
<td>77.43 K</td>
<td>0.03</td>
</tr>
<tr>
<td>273.15 K</td>
<td>273.65 K</td>
<td>0.5</td>
<td>272.55 K</td>
<td>0.6</td>
</tr>
</tbody>
</table>

We have measured the $R(T, P)$ curves for the cooling and warming processes. In this paper we
The superconducting transition during the warming processes, because the warming rate could be made as small as -0.2 K/min, and steady state can easily be achieved, even though we found that the superconducting transition occurs at considerable higher temperatures in both processes.

The temperature dependence of normalized resistance with respect to the resistance values measured at $T_c$ under different pressures up to 4.3 GPa for one sample $\text{Tl}_{1.8}\text{Ba}_{2.0}\text{Ca}_{2.6}\text{Cu}_{3.0}\text{O}_{10+\delta}$ is shown in Fig. 3. The pressures were applied slowly and continuously from zero to 5 GPa. It can be seen that the $T_c$ (onset) is clearly shifted upward with the increase of the applied pressure. When the pressure increases continuously, the $T_c$ rises rapidly and reaches 255.4 K at pressure of 4.3 GPa. The total change in $T_c$ from ambient condition to the high pressure applied can be greater than 126 K. As the pressure is further increased to 4.8 GPa, the $R(T, P)$ curve changes, the behavior of the temperature dependence becomes semiconducting, and there is a marked drop of transition temperature ($T_c \sim 206$ K).

From Fig. 3 we can also see that the resistance ($R$) of the sample decreases with the increase of pressure, which, however, does not reach zero in the range of pressures applied, by analogy with the previous study of superconducting cuprates at high pressure [6,7]. The reason for the nonzero behavior of $R(T, P)$ may be attributed to possible defects and microcracks generated in the sample, as reported by C. W. Chu, et al. [6], but we think it may also come from the possible pressure gradient generated in the anvils, especially at low and very high pressures.

To verify the reproducibility of the effect of high pressure, we have also carried out experiments with decreasing pressure. The results are summarized in Fig. 4, where the transition temperatures $T_c$ are plotted versus pressure for both increasing and decreasing pressures. We found that $T_c(P)$ is a reversible nonlinear function of pressure. The location of the maximum of $T_c$ and the value of $dT_c/dP = 1.7$ K/GPa (at $P = 0$) agree with the previous studies of Tristan Jover et al. [1] and J. G. Lin et al. [2], respectively.

To test the reliability of the above results, we have repeated our experiments several times with other samples cut from the same pellet which was described above. We obtained similar results, one of which is shown in Fig. 5. It can be seen that at a pressure of 3.2 GPa $T_c$ rises to 250 K, while the resistance drops sharply to 13.5% (at 80 K) in comparison with its maximum value. For yet another sample we have obtained $T_c$ (onset) = 153.7 K.

$\text{Fig. 3. Temperature dependence of normalized resistance of the}\quad\text{e}^\text{Tl}_{1.8}\text{Ba}_{2.0}\text{Ca}_{2.6}\text{Cu}_{3.0}\text{O}_{10+\delta}\text{ (Tl-2p4) sample under different pressures.}$

$\text{Fig. 4. Superconducting transition temperature $T_c$ (onset) of}\quad\text{s}^\text{Tl}_{1.8}\text{Ba}_{2.0}\text{Ca}_{2.6}\text{Cu}_{3.0}\text{O}_{10+\delta}\text{ (Tl-2p4) as a function of pressure; } \bullet \text{ as pressure is increased; } \nabla \text{ as pressure is decreased.}$
In summary, the pressure dependence of the superconducting transition temperature in the compound of $\text{Tl}_{1.8}\text{Ba}_{2.0}\text{Ca}_{2.6}\text{Cu}_3\text{O}_{10.8}$ has been determined: the $T_c$ (onset) increases with increasing pressure at a relatively high rate and reaches a maximum value of 255.4 K at a pressure of about 4.3 GPa. External pressure greatly enhances the critical temperature of the oxide superconductor sample. The basic physical reason for this phenomenon is the stronger coupling between the CuO$_2$ planes and the change in free charge concentrations in the superconducting CuO$_2$ layers caused by external pressure. Our experimental investigation on the effect of high pressure on $T_c$ of another pellet of Tl-2223 superconductor is continuing.

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