Enhancement of Interfacial Superconductivity in the Eutectic System \( \text{Sr}_2\text{RuO}_4\)-Ru by Uniaxial Pressure

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Abstract.
We have investigated effects of uniaxial pressure on superconductivity in the 3-K phase in the eutectic system \( \text{Sr}_2\text{RuO}_4\)-Ru. We have found a large enhancement of 3-K phase superconductivity particularly in volume fraction for both in-plane pressure \( P \parallel ab \) and the \( c \)-axis pressure \( P \parallel c \) in contrast to expectations for the 1.5-K phase in pure \( \text{Sr}_2\text{RuO}_4 \). Surprisingly, the effect of the in-plane pressure is even greater than that of the \( c \)-axis pressure. This could be related to the origin of the 3-K phase.

1. Introduction
\( \text{Sr}_2\text{RuO}_4 \) is the first layered perovskite superconductor without copper [1], isostructural to the cuprate high-temperature superconductor \( \text{La}_{2-x}\text{Ba}_x\text{CuO}_4 \). More importantly, taken key experiments together, it is now well believed that the superconductor \( \text{Sr}_2\text{RuO}_4 \) is a spin-triplet superconductor [2].

Amongst a number of remarkable features related to \( \text{Sr}_2\text{RuO}_4 \), an enhancement of the superconducting transition temperature \( T_c \) in the eutectic system \( \text{Sr}_2\text{RuO}_4\)-Ru is rather surprising. The original superconducting phase in pure \( \text{Sr}_2\text{RuO}_4 \) occurs with a sharp transition at a \( T_c \) of 1.5K, called the 1.5-K phase. However, the eutectic system, a two-phase composite structure of a single-crystalline \( \text{Sr}_2\text{RuO}_4 \) matrix and lamellar microdomains of ruthenium metal embedded in it (fig. 1), shows a broad superconducting transition with an enhanced onset of approximately 3 K, called the 3-K phase [3]. On further cooling, the 3-K phase transition is followed by the original superconducting transition in whole \( \text{Sr}_2\text{RuO}_4 \) (the 1.5-K phase). Several experimental facts suggest that 3-K phase superconductivity is filamentary and occurs in the \( \text{Sr}_2\text{RuO}_4 \) side of the interface between \( \text{Sr}_2\text{RuO}_4 \) and Ru [4, 5].

Whilst the origin of the 3-K phase still remains uncertain, Sigrist and Monien’s phenomenological theory [6] within the framework of Ginzburg Landau formalism, which assumes spin-triplet pairing similar to \( \text{Sr}_2\text{RuO}_4 \), successfully describes important aspects of the 3-K phase. Experimentally, the 3-K phase may be considered to be unconventional superconductivity since tunnelling measurements on S/N junctions at interfaces between \( \text{Sr}_2\text{RuO}_4 \) and Ru have observed zero bias conductance peaks [7, 8], which is a hallmark of unconventional superconductivity.

In the present work, we have investigated uniaxial pressure effects on the 3-K phase to obtain insight into the mechanism of the enhancement of the superconducting transition temperature associated with the 3-K phase.
2. Experimental

We used a uniaxial pressure cell with a SQUID (superconducting quantum interference device) magnetometer (MPMS, Quantum Design). The cell is piston-cylinder type, and is made of CuBe apart from the cylinder being made of oxygen-free copper to reduce the background signal. Applied pressures were determined from the forces applied to the samples at room temperature, which was confirmed to show a reasonable agreement with low-temperature pressure determined by the superconducting transitions of tin and lead [10]. SQUID measurements were performed in the order of increasing applied pressure for each sample. The samples used in the present study were grown by a floating-zone method [9] and chosen from a single growth batch. Approximate dimensions of the samples were 1.5 mm × 1.5 mm × 0.3 mm. Uniaxial pressure was applied almost parallel to the shortest dimension.

3. Results and Discussion

Figures 2(a) and (b) show the temperature dependence of the magnetisation (zero field cooling) of Sr$_2$RuO$_4$-Ru crystals for uniaxial pressure parallel to the a-axis ($P_{∥a}$) and to the c-axis ($P_{∥c}$), respectively. The applied DC field of was 2 mT and almost parallel to the direction of the applied pressure. In both figures, diamagnetic signals are observed, which are attributed to the superconductivity associated with the 3-K phase.

Let us compare the (apparent) volume fraction at the lowest temperature 1.8 K between figures 2(a) and (b). The volume fractions at 1.8 K for the $P_{∥a}$ and $P_{∥c}$ samples are about 0.4% and 0.3%, respectively, and are very close to each other. In both of the cases, the application of uniaxial pressure enhances the 3-K phase. However, the strength of the effect significantly differs. At a pressure of 0.4 GPa, in fact, these values increase to 13% (for $P_{∥a}$) and 1% (for $P_{∥c}$) . (Note that the vertical scales in figs. 2(a) and (b) differ by a factor of ten.)

Whilst uniaxial pressure experiments on the 1.5-K phase have not been reported as yet, hydrostatic pressure experiments on the original superconductivity in Sr$_2$RuO$_4$ (1.5-K phase) have been reported, yielding the pressure coefficient of the superconducting transition temperature $dT_c/dP \approx -0.2$ K/GPa [11, 12]. The basic relation in tetragonal symmetry

$$\frac{dT_c}{dP} = \frac{dT_c}{dP_{∥a}} + \frac{dT_c}{dP_{∥b}} + \frac{dT_c}{dP_{∥c}} = 2 \times \frac{dT_c}{dP_{∥a}} + \frac{dT_c}{dP_{∥c}},$$

consequently constrains at least either $dT_c/dP_{∥a}$ or $dT_c/dP_{∥c}$ to be negative, in contrast to results in the present study.
Figure 2. Temperature dependence of the DC magnetisation of Sr$_2$RuO$_4$-Ru in a field of 2 mT (zero field cooling) at different applied uniaxial pressures. (a) for pressure parallel to the $a$-axis. (b) for pressure parallel to the $c$-axis.

In addition to Eq. (1), the use of the Ehrenfest relation involving a discontinuity at $T_c$ in a longitudinal elastic modulus observed in ultrasonic measurements has allowed the dependence of $T_c$ on the uni-axial pressure along the $a$-axis ($dT_c/dP_{\|a}$) and that along the $c$-axis ($dT_c/dP_{\|c}$) to be determined to be negative and positive, respectively [13]. On theoretical grounds, this estimation is supported at least in a qualitative fashion. Under pressure along the $c$-axis, the $\gamma$-band (from the $d_{xy}$ orbital) will be lowered relative to the $\alpha$- and $\beta$-bands in energy. This causes the Fermi energy $E_F$ to approach the van Hove singularity above the Fermi level, leading to an increase in the density of states at the Fermi level [14].

In the context of the above discussion, the results shown in fig. 2 are striking. Both $P_{\|a}$ and $P_{\|c}$ enhance the 3-K phase. Besides, the effect of in-plane pressure is even greater than that of $c$-axis pressure. The latter could be related to the origin of the 3-K phase: The enhancement of the superconductivity associated with the 3-K phase may be due to strain release at the interface between Sr$_2$RuO$_4$ and Ru, as suggested by Sigrist and Monien in ref. [6]. The in-plane pressure will affect the Ru-Ru lattice constant in the $ab$-plane directly whilst the $c$-axis pressure will affect it only indirectly.
4. Summary
We have investigated effects of uniaxial pressure on the interfacial superconductivity in the eutectic system Sr$_2$RuO$_4$-Ru. We have observed that both $P_{\parallel ab}$ and $P_{\parallel c}$ enhance 3-K phase superconductivity in volume fraction, in contrast to expectations for pure Sr$_2$RuO$_4$. The effect of the in-plane pressure is even greater than that of c-axis pressure. This might suggest the importance of strain release at the interface between Sr$_2$RuO$_4$ and Ru in the 3-K phase.

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