Preliminary Scanning Tunneling Spectroscopy Studies of Sr_2RuO_4

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Abstract

We report preliminary scanning tunneling microscopy and spectroscopy (STM/STS) data of Sr_2RuO_4 which is expected to be a spin-triplet superconductor. Several different tunneling spectra were obtained at 4.3 K for single crystalline samples both of 1.5-K (*bulk*) phase and so called 3-K phase. STM/STS measurements at temperatures much lower than the superconducting transition temperature (T_c = 1.5 K) are now in progress with a recently developed ultra-low temperature STM (ULT-STM).

Key words: Sr_2RuO_4; spin-triplet BCS state; STM

In recent years, much attention has been attracted to the unconventional superconducting state of Sr_2RuO_4, a layered perovskite compound. This is because the spin-triplet *p*-wave Cooper pairing is suggested for this material [1]. It is widely accepted that the order parameter is two dimensional analogue of the superfluid ^{3}He A-phase [2]. However, the exact gap function remains still controversial. The microscopic pairing mechanism is further a difficult question to answer, although spin fluctuations seem to be most relevant [3]. Another interesting feature is the existence of "*3-K phase*" where segregated ruthenium islands enhance T_c at most by a factor of two [4].

In general, tunneling spectroscopy measurements should be most useful to determine the superconducting gap structure. So far, the only such a measurement is the Sr_2RuO_4-platinum point contact experiment by Laube *et al.* [5]. They observed zero-bias conductance anomalies which are characteristic to Andreev bound states in *non s*-wave superconductors. However, qualitatively different spectra are also obtained in this experiment, which is probably due to uncontrolled tunneling barriers in various contacts.

In this report, we present preliminary STM/STS data of Sr_2RuO_4 at 4.3 K. This experiment is prototype of forthcoming measurements which will be carried out at temperatures much lower than T_c with the ULT-STM [6].

Single crystals of Sr_2RuO_4 were grown in an infrared image furnace by the floating zone method [7]. The T_c value for the 1.5-K phase sample was determined as 1.42 K from a magnetic susceptibility (χ') data. For the 3-K phase sample, the dissipative component of magnetic susceptibility (χ") starts to increase below 2.45 K and has a peak at 1.39 K.

The experiments were carried out using a home made low temperature STM that works at temperatures down to 1.9 K in ultra high vacuum. The STM head [8] and sample are located in a vacuum can immersed in liquid helium. An annealed silver foil (0.25 mm thick, $RRR = 2600$) is used to thermally connect them to a copper flange of the vacuum can. A 25 μm thick Mylar sheet is inserted between the silver foil and copper flange in order to electrically isolate each other. Just below the STM head, a low-temperature sample cleavage mechanism is attached. After cooling to 4 K and achieving ultra high vacuum environment

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by cryopumping, an originally installed sample was cleaved *in situ* to prepare a clean surface. It was then transferred to the STM head.

Although we could not obtain atomic resolutions in STM images, clear step structures were observed for samples cleaved in parallel to the *ab* plane. The step height (0.64 nm) corresponds to a half of the unit cell height indicating that the cleaved surface is SrO plane as was reported by other researchers [9].

We made preliminary STS measurements at various different points of the cleaved surface of the 1.5-K phase sample (Fig. 1) at a temperature (T = 4.3 K) higher than T_c. Each tunneling spectrum was obtained by averaging raw data on 625 grid points within an area of 3 nm×3 nm in order to improve the signal to noise ratio. This area was so chosen as to be smaller than a minimum terrace size (∼10 nm). A semiconducting spectrum with an energy gap (Δ) of 20 - 40 mV was obtained at most locations (solid circles in the figure). Note that the gap width is much larger than the energy scale for the superconductivity (∼0.2 mV). We also observed another type of spectrum with non zero conductance at the fermi level (open circles) occasionally. These observations remind us the facts that the cleaved surface of $Bi_2Sr_2CaCu_2O_{8+\delta}$, a high T_c cuprate, is semiconducting BiO plane and that the superconducting gap was observed within the semiconducting gap [10] when the tip-sample distance is close enough. This may suggest a possibility to detect the superconducting gap of Sr_2RuO_4 in a similar scenario if we cool the sample through T_c.

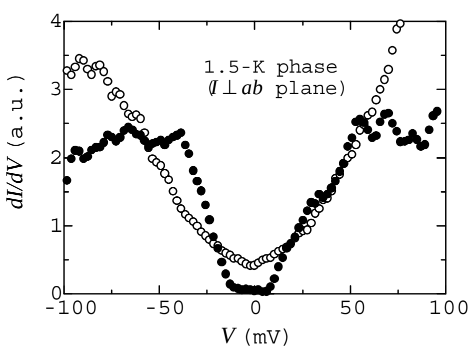

Fig. 1. Two typical tunneling spectra of the 1.5-K phase of Sr_2RuO_4 cleaved in parallel to the *ab* plane (T = 4.3 K, $V = 0.05$ V, $I = 0.1$ nA).

On the other hand, STS data for the 3-K phase are more complicated (Fig. 2). In this case, the sample was cleaved perpendicular to the *ab* plane. Observed spectra can be classified into three different types. Two of them (closed and open circles in the figure) are rather similar to those for the 1.5-K phase, although they have more metallic characters. This may be explained by that a more direct tunneling to the conducting RuO_2 plane is possible in this configuration. The third type of spectrum (crosses) has more semiconducting characters than any others.

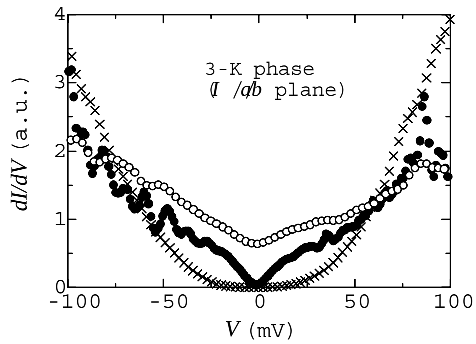

Fig. 2. Three typical tunneling spectra of the 3-K phase of Sr_2RuO_4 cleaved perpendicular to the *ab* plane (T = 4.4 K, $V = 0.1$ V, $I = 2$ nA).

So far, the lack of atomic resolution and precise controlling of the tip-sample distance prevents us from analyzing these preliminary STS data quantitatively. This problem will be soon resolved by more comprehensive measurements using the ULT-STM [6] with a much higher spatial resolution. Such measurements are now under going for the superconducting phases of Sr_2RuO_4 at temperatures down to 160 mK and in magnetic fields up to 6 T.

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