Transverse Elastic Moduli in Spin-Triplet Superconductor Sr_2RuO_4

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Abstract

Transverse ultrasonic measurements have been performed on a single crystal of Sr_2RuO_4 across the superconducting transition temperature T_c (~ 1.40 K). We found an indication of a jump at T_c in transverse elastic modulus C_{66}, which is attributable to the coupling between strains and two-dimensional order parameters(OP) with broken time-reversal symmetry. This leads to additional evidence for the spin-triplet superconductivity with a two-dimensional OP.

Key words: Sr_2RuO_4; Ultrasound; Transverse Elastic Moduli; Two-Dimensional Order Parameter; Broken Time-Reversal Symmetry

The ruthenate Sr_2RuO_4 has the layered perovskite structure of K_2NiF_4-type with a tetragonal crystal point group D_{4h}. Intense attention has been paid to the ruthenate not only because it is the first example [1] of the non-cuprate layered-perovskite superconductor but also because it shows spin-triplet superconductivity which was proven by the spin susceptibility [2] essentially unchanged across the superconducting transition temperature T_c. Moreover muon-spin-rotation measurements [3] claim that spontaneous magnetic moment appears in the superconducting state, suggesting a pairing state with broken time-reversal symmetry. Therefore, the symmetry of superconductivity is likely to be of the chiral p-wave with basically in the form of the superconducting energy gap $\boldsymbol{d}(\boldsymbol{k}) = \hat{\boldsymbol{z}}(k_x \pm \mathrm{i}k_y)$ and in-plane equal-spin pairing [4,5]. Moreover the power-law temperature dependence of the ultrasonic attenuation [6] suggested the existence of nodes in the gap function of Sr_2RuO_4. This state has a two-component order parameter(OP) which belongs to the two-dimensional representation E_u. Recently, Taillefer, Lupien, and Walker [7] pointed out that transverse elastic moduli in Sr_2RuO_4 may show a discontinuous jump at T_c. If we find the jump at T_c in the transverse elastic moduli, it would constitute additional evidence for the p-wave superconductivity with the two-dimensional OP from ultrasonic experiments [8]. In order to investigate the symmetry of superconductivity in Sr_2RuO_4, we have measured the temperature dependence of transverse elastic modulus C_{66}.

The single crystal used in this study was prepared by a floating-zone method using an infrared image furnace [9]. We determined $T_c \simeq 1.40$ K for the present crystal from the onset temperature in elastic modulus, which agrees well with that in ac-susceptibility. The change in sound velocity was measured by a phase-comparison type pulse-echo technique. We measured the in-plane transverse sound velocity propagating along the [100] with the [010] polarization (T1 mode) which corresponds to the transverse elastic modulus C_{66}. We used ultrasound of 50 MHz generated and detected by a pair of $LiNbO_3$ transducers. The elastic modulus C_{66} was evaluated from the velocity v using the equation $C_{66} = \rho v^2$, where ρ is the mass density($= 5.888$ g/cm ^{3} at 15 K [10]).

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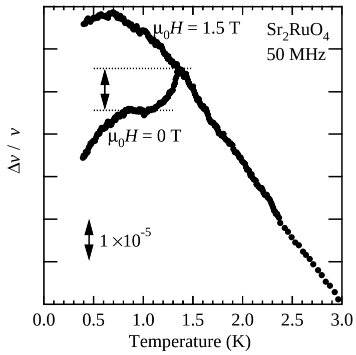

Fig. 1. The temperature dependence of sound velocity shown for both the superconducting state at 0 T and the normal state at 1.5 T. The magnetic field was applied along the c axis to kill the superconductivity. The jump of C_{66} at T_c is indicated by the arrow line, the magnitude of which was as small as $\Delta v/v = 1 \times 10^{-5}$.

Temperature dependence of the sound velocity of T1 mode below 3 K in magnetic field $\mu_0 H$ is displayed in Fig. 1. We determined the absolute value of sound velocity to be 2.6 $\times 10^3$ m/s at 4.2 K by directly measuring the time interval between the subsequent echo signals. In consequence, we obtained the approximate value of 40 GPa for the elastic modulus C_{66} at 4.2 K. The sound velocity in the superconducting state is evidently small compared with that in the normal state.

For superconductors with a *one-dimensional* OP, the first-order derivative of T_c with respect to shear strain ε_Γ is absent since $+\varepsilon_\Gamma$ and $-\varepsilon_\Gamma$ give the same energy state. Consequently the transverse elastic modulus exhibits no jump at T_c. In contrast, for a superconductor with a *two-dimensional* OP with broken time-reversal symmetry, it is not obvious whether $+\varepsilon_\Gamma$ and $-\varepsilon_\Gamma$ always give the same energy state or not. We briefly discuss the behavior of elastic moduli in Sr_2RuO_4 with a single set of order parameters $\boldsymbol{d}(\boldsymbol{k}) = \hat{\boldsymbol{z}}(\eta_x k_x + \eta_y k_y)$. The order parameter has two components, belonging to the irreducible representations E_u, and its symmetric square is

$$[E_u]^2 = A_{1g} + A_{2g} + B_{1g} + B_{2g}. \quad (1)$$

For point group D_{4h}, one has the following strain representations: $A_{1g}(\varepsilon_{xx} + \varepsilon_{yy})$, $A_{1g}(\varepsilon_{zz})$, $B_{1g}(\varepsilon_{xx} - \varepsilon_{yy})$, $B_{2g}(\varepsilon_{xy})$ and $E_g(\varepsilon_{yz}, \varepsilon_{zx})$, corresponding to $(C_{11} + C_{12})$, C_{33}, $(C_{11} - C_{12})$, C_{66} and C_{44}, respectively. Therefore the coupling terms of the free energy read

$$\begin{aligned} F_{so} = & (g_{A_{1g}}(\varepsilon_{xx} + \varepsilon_{yy}) + g'_{A_{1g}}\varepsilon_{zz})(|\eta_x|^2 + |\eta_y|^2) \\ & + g_{B_{1g}}(\varepsilon_{xx} - \varepsilon_{yy})(|\eta_x|^2 - |\eta_y|^2) \\ & + g_{B_{2g}}\varepsilon_{xy}(\eta_x^*\eta_y + \eta_x\eta_y^*), \end{aligned} \quad (2)$$

where g_Γ is coupling constant with symmetry Γ. Because there is no coupling linear in the strain ε_{yz}, ε_{zx} but quadratic in OP in the free energy, the transverse elastic modulus C_{44} exhibits no jump at T_c in the two dimensional OP [11]. It is not obvious whether $(C_{11} - C_{12})/2$ should exhibit a jump at T_c from this discussion alone since it is not necessarily $|\eta_x|^2 = |\eta_y|^2$. In contrast, the elastic modulus C_{66} should show a step-like decrease at T_c. In Fig. 1, we can indeed see a jump-like behavior at T_c. The roughly estimated jump is smaller than 8 $\times 10^{-4}$ GPa, which is shown in Fig. 1. From the magnitude of the jumps at T_c, $|\Delta C_{11}(T_c)| \sim 1.5 \times 10^{-2}$ and $|\Delta C_{33}(T_c)| \leq 1 \times 10^{-3}$ GPa [12]; it is expected that $|(g_{A_{1g}} + g_{B_{1g}})| > |g'_{A_{1g}}| \geq |g_{B_{2g}}|$.

In summary, we measured the transverse elastic modulus C_{66} across T_c in Sr_2RuO_4, and observed a jump-like behavior at T_c. We briefly discussed the behavior of elastic moduli with two-component OP, and we pointed out that C_{66} is likely to jump at T_c. If we confirm a jump more clearly in the transverse elastic modulus, it constitutes additional evidence for the p-wave superconductivity with the two-dimensional OP from the ultrasonic experiments.

This work was in part by supported by Grant-in-Aids both for Scientific Research and COE Research (No. 13CE2002) from the Ministry of Education, Culture, Sports, Science and Technology of Japan. We acknowledge Manfred Sigrist for useful information.

References

[1] Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J. G. Bednorz and F. Lichtenberg, Nature **372** (1994) 532.

[2] K. Ishida, H. Mukuda, Y. Kitaoka, K. Asayama, Z. Q. Mao, Y. Mori and Y. Maeno, Nature **396** (1998) 658.

[3] G. M. Luke, Y. Fudamoto, K. M. Kojima, M. I. Larkin, J. Merrin, B. Nachumi, Y. J. Uemura, Y. Maeno, Z. Q. Mao, Y. Mori, H. Nakamura and M. Sigrist, Nature **394** (1998) 558

[4] M. Sigrist, D. Agterberg, A. Furusaki, C. Honerkamp, K. K. Ng, T. M. Rice, and M. E. Zhitomirsky, Physica C **317-318** (1999) 134.

[5] Y. Maeno, S. NishiZaki, and Z. Q. Mao, J. Supercond. **12** (1999) 535.

[6] C. Lupien, W. A. MacFarlane, Cyril Proust, Louis Taillefer, Z. Q. Mao and Y. Maeno, Phys. Rev. Lett. **86** (2001) 5986.

[7] L. Taillefer; private communication.

[8] M. Sigrist, Prog. Theo. Phys. **107** (2002) 917.

[9] Z. Q. Mao, Y. Maeno and H. Fukazawa, Mater. Res. Bull. **35** (2000) 1813.

[10] O. Chmaissem, J. D. Jorgensen, H. Shaked, S. Ikeda and Y. Maeno, Phys. Rev. B **57** (1998) 5067.

[11] W. Rehwald, Adv. in Phys. **22** (1973) 721.

[12] N. Okuda, T. Suzuki, Z. Q. Mao, Y. Maeno and T. Fujita, J. Phys. Soc. Jpn. **71** (2002) 1134.