平成 17－21 年度
文部科学省科学研究費補助金「特定領域研究」

「スーパークリーン物質で実現する新しい量子相の物理」
A04 班　スピン三重項　小研究会
講演概要集

平成 18 年 12 月 17 日（日）
於　兵庫県立 淡路夢舞台国際会議場
〒656-2306 兵庫県淡路市夢舞台 1 番地
Tel：0799-74-1020　Fax：0799-74-1021

Opening

8:30-8:35 Y. Maeno (Kyoto Univ.)

8:35-8:45 H. Yaguchi (Kyoto Univ.)

Morning Session: Physics of the d-vector

Chair: H. Yaguchi (Kyoto Univ.)

Experiment (1)

8:45-9:15 (A-1) K. Ishida (Kyoto Univ.)
Review of NMR studies on Sr_2RuO_4

9:15-9:35 (A-2) K. Tenya (Hokkaido Univ.)
Static magnetization study of Sr_2RuO_4

9:35-9:55 (A-3) F. Nakamura (Hiroshima Univ.)
Elastic moduli of Sr_2RuO_4 in magnetic fields

9:55-10:10 Coffee break

Chair: Y. Tanaka (Nagoya Univ.)

Experiment (2)

10:10-10:30 (A-4) K. Deguchi (Nagoya Univ.)
Specific heat measurements of Sr_2RuO_4

10:30-10:50 (A-5) H. Yaguchi (Kyoto Univ.)
Superconducting double transition and tunnelling spectroscopy in Sr_2RuO_4 and its eutectic system Sr_2RuO_4-Ru

Theory

10:50-11:10 (A-6) M. Udagawa (Univ. Tokyo)
Superconducting multiphase in Sr_2RuO_4

11:10-11:30 (A-7) M. Ichioka (Okayama Univ.)
Suppression of superconductivity at higher fields in Sr_2RuO_4

11:30-11:50 (A-8) H. Ikeda (Kyoto Univ.)
Magnetic properties in the normal and superconducting states in Sr_2RuO_4

Chair: K. Ishida (Kyoto Univ.)

11:50-12:20 Discussion

12:20-13:10 Lunch

Afternoon Session: Odd-frequency pairing state

Chair: Kambara (Univ. Tokyo)

13:10-13:40 (P-1) Y. Tanaka (Nagoya Univ.)
Odd-frequency pairing state in superconducting junctions

13:40-14:00 (P-2) K. Miyake (Osaka Univ.)
Review on odd-frequency pairing state

14:00-14:20 (P-3) Y. Fuseya (Univ. Tokyo)
Possible existence of the odd-freqency superconductivity

14:20-14:40 Coffee break

Chair: Ishida (Kyoto Univ.)

14:40-15:00 (P-4) Y. Asano (Hokkaido Univ.)
Josephson current by odd-frequency pairs

15:00-15:20 (P-5) T. Yokoyama (Nagoya Univ.)
Odd-frequency pairing through ferromagnetic junctions

15:20-15:40 (P-6) K. Nagai (Hiroshima Univ.)
Quasi-classical Theory of Surface and Interface Effects on Anisotropic Fermi Superfluids

15:40-15:55 (P-7) S. Kashiwaya (AIST)
Proximity effect due to odd frequency pairing

15:55-16:10 (P-8) H. Kambara (Univ. Tokyo)
STM/STS study of Sr_2RuO_4

Chair: Y. Tanaka (Nagoya Univ.)

16:10-16:40 Discussion

Closing

16:40-16:50 O. Ishikawa (Osaka city Univ.)

開会

8:30-8:35　はじめに　前野悦輝（京大）

8:35-8:45　趣旨説明　矢口　宏（京大）

午前のセッション「ｄベクトルの物理」

座長：矢口　宏（京大）

【実験１】

8:45-9:15　(A-1)　石田憲二（京大）
ナイトシフト、温度磁場相図中のｄベクトルの回転

9:15-9:35　(A-2)　天谷健一（北大）
静磁化、超伝導多重相の実験

9:35-9:55　(A-3)　中村文彦（広大）
超音波、超伝導多重相の実験

9:55-10:10　コーヒー・ブレーク

座長：田仲由喜夫（名大）

【実験２】

10:10-10:30　(A-4)　出口和彦（名大）
比熱、超伝導二段転移、上部臨界磁場の抑制の実験

10:30-10:50　(A-5)　矢口　宏（京大）
準粒子トンネル効果と Sr_2RuO_4 共晶体における超伝導二段転移

【理論】

10:50-11:10　(A-6)　宇田川将史（東大）
超伝導二段転移

11:10-11:30　(A-7)　市岡優典（岡大）
上部臨界磁場の抑制

11:30-11:50　(A-8)　池田浩章（京大）
常伝導・超伝導状態における磁気的性質

座長：石田憲二（京大）

11:50-12:20　自由討論

12:20-13:10　昼食

午後のセッション「奇周波数超伝導のペア状態」

座長：神原　浩（東大）

13:10-13:40　(P-1)　田仲由喜夫（名大）
奇周波数超伝導のペアと超伝導接合

13:40-14:00　(P-2)　三宅和正（阪大）
奇周波数超伝導のペアの歴史

14:00-14:20　(P-3)　伏屋雄紀　（東大）
奇周波数超伝導の存在可能性

14:20-14:40　コーヒー・ブレーク

座長：石田憲二（京大）

14:40-15:00　(P-4)　浅野泰寛（北大）
奇周波数ペアの担うジョセフソン電流

15:00-15:20　(P-5)　横山毅人（名大）
奇周波数ペアと強磁性接合

15:20-15:40　(P-6)　永井克彦（広大）
近接効果の理論
準古典論による異方的フェルミ超流体における界面効果

15:40-15:55　(P-7)　柏谷　聡（産総研）
ルテニウム系での近接効果の実験の現状

15:55-16:10　神原　浩（東大）
近接効果と STM/STS

座長：田仲由喜夫（名大）

16:10-16:40　自由討論とまとめ

閉会

16:40-16:50　おわりに　　石川修六（阪市大）

Review of NMR Studies on Sr_2RuO_4

K. Ishida,[1,2] H. Murakawa,[1] Y. Aono,[1] and Y. Maeno[1]

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[2]*International Innovation Center, Kyoto University, Sakyo-ku, Kyoto 606-8501*

In our presentation, we will review our Ru- and ^{17}O-NMR studies in Sr_2RuO_4, which have been performed since the discovery of superconductivity in this compound. One of the advantages of the NMR experiments is that microscopic spin susceptibility can be measured from the Knight-shift measurements. This is the most accurate way to measure the spin susceptibility in the superconducting state. In order to investigate the direction of the superconducting **d** vector under magnetic fields and in a zero field, we have measured Knight shift in various magnitude of fields and in different directions as shown in Fig. 1. For this purpose, we had to observe the Ru NMR signal in small fields less than 1 kOe, and observed the signal by using nuclear-quadrupole-resonance (NQR) spectra. We have measured the Knight shift along the c axis and the RuO_2 plane, and it was invariant across T_c in both directions. These results suggest that the effect to fix the spins of the spin-triplet Cooper pairs is weak in Sr_2RuO_4, so that the spin direction is changed by the small magnetic fields applied for the Knight-shift measurements. We discuss possible interactions to fix the **d**-vector, which should be taken into account in Sr_2RuO_4. We will also review the Knight-shift results in spin-triplet superconductor UPt_3, and compare the Knight-shift results with the results obtained in Sr_2RuO_4.

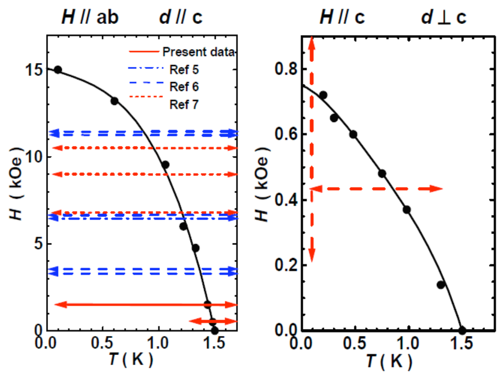

Fig.1: Magnetic fields and temperature range of Knight shift measurements performed so far are shown. Ru-NMR and 17O-NMR measurements were displayed by the red and blue lines, respectively. Under H // c, Knight-shift measurements were performed using only Ru signal.

Static Magnetization Study of Sr_2RuO_4

K. Tenya,[1] R. Yamahana,[1] M. Yokoyama,[2] H. Amitsuka,[1] K. Deguchi,[3] and Y. Maeno[4,5]

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[2]*Department of Materials and Biological Sciences, Ibaraki University, Mito 310-8512*
[3]*Department of Physics, Graduate School of Science, Nagoya University, Nagoya 454-8602*
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Various experimental facts strongly support the spin-triplet superconductivity with ***d*//*z*** in the layered ruthenate Sr_2RuO_4. The suppression of upper critical field and the appearance of novel high-field phase for $H \perp [001]$, however, seem to contradict with the above scenario. We have investigated the *H*-*T* phase diagram of the upper critical field H_{c2} and novel high-field phase in Sr_2RuO_4 by means of the magnetization and magnetic torque measurements.

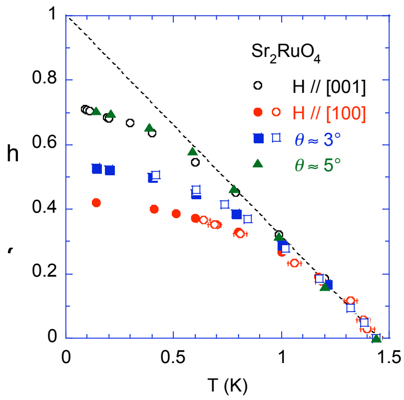

FIG. 1: Temperature dependence of the reduced upper critical field *h*.

Figure 1 shows temperature dependence of the reduced upper critical field h $(=H_{c2}(T)/[T_c dH_{c2}/dT]_{T=Tc})$ in the various field directions, where θ is the tilted angle between field and [100] directions. While no paramagnetic suppression of the superconductivity is found at $\theta > 5^\circ$, the strong suppression of H_{c2} together with the appearance of novel high-field phase are observed below ~ 1 K at $\theta \leq 3^\circ$.

The anomalous vortex-pinning behaviors such as successive flux-jumps and second magnetization peak at low fields for *H*//[100] are also reported.

A-3

Elastic Moduli of Sr_2RuO_4 in Magnetic Fields

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As a crucial test of triplet superconductivity of Sr_2RuO_4 (SRO), many efforts are performed to find the field-induced multi phases with the different order parameters. We believe that ultrasonic measurement is a suitable technique to explore the anomalies in the temperature-field phase diagram. We have measured the elastic moduli C_{11}, $(C_{11} - C_{12})/2$, C_{44} and C_{66} as a function of the field along the *a* axis. We have observed a step like change in the field dependence of C_{66} at the upper critical fields is as an evidence of the triplet superconductivity with two-dimensional order parameter. However, we have not yet observed the field-induced new phases as is reported by Tenya *et al* [1]. More improving the sensitivity of our ultrasonic measurement will make possible to conform the existence of the new phase.

A-4

Specific heat measurements of Sr_2RuO_4

K. Deguchi[1] and Y. Maeno[2]

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[2] *Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan.*

The layered perovskite superconductor Sr_2RuO_4 (T_c = 1.5 K) is considered as an unconventional spin-triplet superconductor with strong quasi-two dimensionality [1]. Its superconductivity exhibits pronounced unconventional features [2]. For its superconducting symmetry, experimental results strongly suggest the spin-triplet pairing with time-reversal symmetry breaking, or chirality, associated with the Cooper-pair orbital moment. A number of experiments revealed the existence of the nodal structure in the superconducting gap and urged the strong orbital dependence of the gap amplitude characterizing each of the three cylindrical Fermi surfaces [3,4]. As a characteristic of unconventional superconductivity in Sr_2RuO_4, *multiple superconducting phases emerged*.

The studies of specific heat and thermal conductivity as a function of magnetic field orientation were performed at low temperatures. In this presentation, we will focus on two important issues for the magnetic field precisely parallel to the RuO_2 plane, which appear to be intimately related to each other. First, we show the evidence for strong limiting of the upper critical field H_{c2}. Second, we present thermodynamic evidence for the second superconducting phase in magnetic fields. The latter phenomenon most likely reflects the internal degrees of freedom of the Cooper pair, but at the same time, it appears to be a consequence of the unusual limiting of H_{c2} [5].

[1] Y. Maeno *et al.*, Nature **372**, 532 (1994)
[2] A.P. Mackenzie and Y. Maeno, Rev. Mod. Phys. **75**, 657 (2003).
[3] K. Deguchi *et al.*, Phys. Rev. Lett. **92**, 047002 (2004).
[4] K. Deguchi *et al.*, J. Phys. Soc. Jpn. **73**, 1313 (2004).
[5] K. Deguchi *et al.*, J. Phys. Soc. Jpn. **71**, 2839 (2002).

Superconducting double transition and tunnelling spectroscopy in Sr_2RuO_4 and its eutectic system Sr_2RuO_4-Ru

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In superconductor/normal-metal (S/N) junctions involving unconventional superconductors, a zero bias conductance peak (ZBCP) may be observed as a consequence of the formation of Andreev bound states at the interface. We have achieved Sr_2RuO_4/Ru junctions on a eutectic crystal that consists of Sr_2RuO_4 and Ru micro-inclusions using a micro-fabrication technique [1]. Such eutectic crystals show an enhanced superconducting transition at about 3 K, called the 3-K phase [2], while pure Sr_2RuO_4 shows a superconducting transition at about 1.5 K. The tunnelling spectra of a junction exhibit a ZBCP in the 3-K phase of Sr_2RuO_4. The onset of the ZBCP occurs at a lower field and a lower temperature than the onset of 3-K phase superconductivity, and, we propose, may be used to determine the onset of a time-reversal symmetry breaking (or chiral) state.

This transition to the chiral state is at least in a qualitative fashion very similar to the long-sought superconducting double transition in Sr_2RuO_4, which would be a hallmark of spin-triplet superconductivity, discussed by Agterberg [3]. We will elaborate on the similarity along the line of Sigrist and Monien's phenomenological theory [4] based on the Ginzburg Landau formalism.

[1] M. Kawamura, H. Yaguchi, N. Kikugawa, Y. Maeno, and H. Takayanagi, J. Phys. Soc. Jpn. **74**, 531 (2005).
[2] Y. Maeno, T. Ando, Y. Mori, E. Ohmichi, S. Ikeda, S. NishiZaki, and S. Nakatsuji, Phys. Rev. Lett. **81**, 3765 (1998).
[3] D.F. Agterberg, Phys. Rev. Lett. **80**, 5184 (1998).
[4] M. Sigrist and H. Monien, J. Phys. Soc. Jpn. **70**, 2409 (2001).

A-6

Superconducting multiphase in Sr_2RuO_4

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Sr_2RuO_4 shows a superconducting multiphase under a magnetic field parallel to the superconducting plane. In the neighborhood of H_{c2}, several thermodynamic quantities such as the specific heat show anomaly, implying an existence of phase transition[1]. On the other hand, magnetization kink has been observed at intermediate magnetic field ($H \sim 0.5H_{c2}$)[2]. Therefore, the superconducting phase of Sr_2RuO_4 seems to be divided into three phases.

We would like to propose that the number of phases is not three but two. The anomaly near H_{c2} is not a phase transition, but a crossover between non-unitary $k_y(\mathbf{d_z} - ia\mathbf{d_y})$ state (a<1) and unitary $k_y\mathbf{d_z}$ state. Non-unitary state occurs at H_{c2} since the density of states of up-spin and down-spin electrons are made unequal due to Zeeman shift. Usually, this effect is suppressed because the d vector is strongly fixed. However, in the case of Sr_2RuO_4, d vector changes its direction by a tiny magnetic field[3], then the non-unitary state can be stabilized[4].

On the other hand, the magnetization kink at intermediate magnetic field can be understood as a phase transition between $k_y\mathbf{d_z}$ state and $(k_x \pm ik_y)\mathbf{d_z}$, which is proposed by Agterberg[5].

We have studied the crossover and the Agterberg's phase transition by the quasiclassical theory and obtained the phase diagram consistent with the experiments.

[1] A.P.Mackenzie and Y.Maeno, Rev. Mod. Phys. **75**, 657 (2003)
[2] K. Tenya et al., J. Phys. Soc. Jpn. **75**, 023702 (2006)
[3] H. Murakawa et al., Phys. Rev. Lett. **93**, 167004 (2004)
[4] M. U et al., J. Phys. Soc. Jpn **74**, 2905 (2005)
[5] D. F. Agterberg, Phys. Rev. Lett. **80**, 5184 (1998)

Suppression of superconductivity at higher fields in Sr_2RuO_4

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Quantitative estimate of the paramagnetic effect as well as the diamagnetic effect is important to understand the behavior of physical quantities in the mixed state of superconductors.

We study the vortex states under strong paramagnetic effect in the case of pairing between up- and down-spin electrons. By the selfconsistent calculation of pair potential and vector potential based on the quasiclassical theory, we demonstrate the significant contribution of the paramagnetic pair breaking and the induced paramagnetic moment around the vortex core, quantitatively estimating the magnetic field (B)-dependence of low temperature specific heats $\gamma(B)$, Knight shift $\chi(B)$, magnetization $M(B)$ and the flux line lattice (FLL) form factor. In Fig.1, we show the magnetization curve $M(B)$ when the paramagnetic effect is large.

Comparing with these calculated results, we discuss the experimental data of $\gamma(B)$ and $M(B)$ under parallel fields in Sr_2RuO_4, focusing the suppression of superconductivity at higher fields.

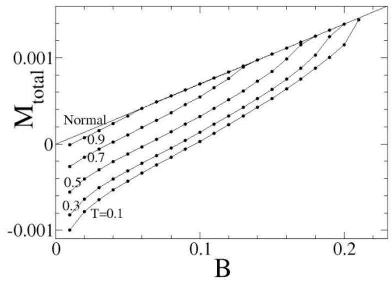

FIG.1: Magnetic field dependence of magnetization $M(B)$, including paramagnetic and diamagnetic contributions, at T/T_c=0.1, 0.3, 0.5, 0.7, 0.9 and 1.0 in the presence of paramagnetic depairing effect. The magnetization curve rapidly approaches the normal state value at higher fields.

A-8

Magnetic properties in the normal and superconducting states in Sr_2RuO_4

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On understanding the superconductivity in Sr_2RuO_4, it is important to clarify the magnetic properties. Up to now, he Knight shift in the NMR experiment does not decrease in any directions below the superconducting transition temperature (T_c). This indicates that the orientational energy of the order parameter field is less than energy corresponding to the applied magnetic field (*200G*). In addition, temperature dependence of the in-plane $1/T_1$ in the NQR experiment is different from that of out-of-plane below T_c.

In order to explain these behavior, we investigate the magnetic properties in the normal and superconducting states in Sr_2RuO_4 by carrying out the perturbative approach with the spin-orbit interaction.

P-1

Odd-frequency pairing state in superconducting junctions

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2Faculty of Science and Technology, University of Twente, The Netherlands
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We show that odd-frequency pairing state is induced very generally in the non-uniform superconducting system. In general, the possible symmetry classes in a superconductor which are consistent with the Pauli principle are even-frequency spin-singlet even-parity (ESE) state, even-frequency spin-triplet odd-parity (ETO) state, odd-frequency spin-triplet even-parity (OTE) state and odd-frequency spin-singlet odd-parity (OSO) state. We studied about the ballistic normal metal / superconductor junctions for ESE and ETO state using the quasiclassical Green's function formalism. It is shown that the ESE (ETO) pair potential in a superconductor induces the OSO (ETO) pair amplitude in the absence of spin-flip scattering at the interface. The appearance of the midgap Andreev resonant states due to the sign change of the anisotropic pair potential at the interface is reinterpreted in terms of strong enhancement of the odd-frequency pair amplitude. We also studied diffusive normal metal (DN)/ superconductor junctions. It is clarified that when the symmetry of the superconductor is spin-triplet, the resulting pair amplitude in DN is OTE state. The generation of the OTE state in the DN attached to the ETO p-wave superconductor is of particular interest in the relevance to the novel proximity effect in Sr_2RuO_4 junctions.

[1]Y. Tanaka et al, cond-mat/0609566, 0610017.

P-2

Review on odd-frequency pairing state

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Division of Materials Physics, Department of Materials Engineering Science,
Graduate School of Engineering Science, Osaka University, Toyonaka 560-8531, Japan.

A history of development of an idea of the so-called odd-frequency pairing is briefly reviewed [1-6]. The odd-energy gap, a variant of odd-frequency gap, is also discussed [7-11].

[1] V. L. Berezinskii, Sov.-Phys. JETP **20** (1974) 287.
[2] A. Balatsky and E. Abrahams, Phys. Rev. B **45** (1992) 13125.
[3] E. Abrahams, A. Balatsky, J. R. Schrieffer and P. B. Allen, Phys. Rev. B **47** (1993) 513.
[4] M. Vojta and E. Dagotto, Phys Rev B **59** (1999) 713.
[5] Y. Fuseya, H. Kohno and K. Miyake, J. Phys. Soc. Jpn. **72** (2003) 2914.
[6] E. Abrahams, A. Balatsky, D. J. Scalapino and J. R. Schrieffer: Phys. Rev. B **52** (1995) 1271.
[7] M. H. Cohen, Phys. Rev. Lett. **12** (1964) 664.
[8] S. Nakajima, Prog. Theor. Phys. **32** (1964) 871.
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[10] F. Mila and E. Abrahams, Phys. Rev. Lett. **67** (1991) 2379.
[11] M. Dobroliubov, E. Langmann and P.C. E. Stamp, Europhys. Lett. **26** (1994) 141.

Possible Existence of the Odd-Frequency Superconductivity

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[2]*Department of Physical Science, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531*

We investigate a possible realization of the odd-frequency superconductivity (odd-SC), whose gap function is odd in frequency. It is revealed that, for the odd-SC, the ferromagnetic fluctuation enhances the instability of even-parity (e.g., *s*-, *d*-wave) triplet pairing, and the antiferromagnetic one enhances that of odd-parity (e.g., *p*-, *f*-wave) singlet pairing. (Table.1) Strongly-retarded interactions are the necessary conditions that the odd-SC prevails over the conventional even-frequency superconductivity (even-SC). Whether the odd-SC practically realize depends on the details of the pairing interaction or the Fermi surface.

ferro.	*s*-wave	*p*-wave	*d*-wave
singlet	×	×	×
triplet	○	○	○

antiferro.	*s*-wave	*p*-wave	*d*-wave
singlet	×	○	○
triplet	○	×	×

TABLE 1: Possible pairing symmetries for ferromagnetic interaction (upper table) and for antiferromagnetic one (lower table). The highlighted cells indicate the ***odd-frequency*** pairing.

In order to investigated a concrete possibility of the odd-SC, we solve the gap equation with the practical interactions for the heavy fermion Ce-compounds. The ***p*-wave *singlet* odd-SC** is realized in the vicinity of the antiferromagnetic quantum critical point on both the paramagnetic and the antiferromagnetic sides. The calculated gap function has no gap on the Fermi surface, so that the physical quantities show gapless behaviors. This can give a qualitative understanding of the gapless behaviors of NQR relaxation rate and specific heat on $CeCu_2Si_2$ and $CeRhIn_5$.

[1] Y. Fuseya, H. Kohno and K. Miyake: J. Phys. Soc. Jpn. 72 (2003) 2914.

P-4

Josephson current by odd-frequency pairs

Y. Asano,[1] Y.Tanaka,[2] and S. Kashiwaya[3]

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[3]*National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, 305-8568*

We discuss the anomalous Josephson effect due to the odd-frequency Cooper pairs. First we consider p-wave superconductor/ normal metal / p-wave superconductor (p/N/p) junctions, where a normal metal is in the diffusive transport regime due to impurity scattering. The pairs can penetrate into a normal metal by the proximity effect. Although original symmetry of pairs in superconductors is p-wave, pairing function in a normal metal is isotropic s-wave symmetry due to diffusive impurity scattering. As a consequence, Cooper pairs have the odd-frequency symmetry and are responsible for anomalous Josephson current at low temperatures[1].

Second we consider s-wave superconductor / half metal / s-wave superconductor (s/HM/s) junctions. The electric structures of a half metal are metallic for one spin direction and insulating for the other. Thus the spin-flip scattering at the junction interface is required for the Josephson coupling. The spin-flip scattering causes s-wave spin-triplet pairs in a HM, which also has odd-frequency symmetry. In both cases, odd-frequency pairs results in the large enhancement of the quasiparticle density of states in diffusive metals.

[1] Y. Asano, Y. Tanaka, and S. Kashiwaya, Phys. Rev. Lett. 96, 097007 (2006)
[2] Y. Asano, Y. Tanaka, and A. A. Golubov, cond-mat/0609566

P-5

Odd-frequency pairing through ferromagnetic junctions

T. Yokoyama[1], Y. Tanaka,[1] and A. A. Golubov[2]

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Using the quasiclassical Green's function formalism, we study the condition for the formation of zero-energy peak (ZEP) in the local density of states (LDOS) in a diffusive ferromagnet (DF) attached to a spin-singlet s-wave superconductor[1], and its relevance to the odd-frequency spin-triplet even parity (OTE) superconductivity[2]. We show that the magnitude of the OTE component of the pair amplitude is enhanced with the increase of the exchange field in DF. When the OTE component is dominant at low energy, the resulting LDOS in DF has a ZEP. We demonstrate that the appearance of the dominant OTE component of the pair amplitude is the physical reason of the emergence of the ZEP of LDOS.

[1] T. Yokoyama, Y. Tanaka, and A. A. Golubov, Phys. Rev. B **72**, 052512 (2005); Phys. Rev. B **73**, 094501 (2006).
[2] T. Yokoyama, Y. Tanaka, and A. A. Golubov, cond-mat/0610608.

P-6

Quasi-classical Theory of Surface and Interface Effects on Anisotropic Fermi Superfluids

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Some aspects of surface and interface effects in anisotropic Fermi superfluids are discussed on the basis of quasi-classical theory. Enhancement of surface magnetization owing to the surface bound states are discussed. Some comments are also given on the behavior of odd-frequency order parameter in proximity contact systems.

Proximity effect due to odd frequency pairing

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Recent theory by Tanaka *et al.* predicts the presence of the odd frequency pairing in various types of anisotropic superconductors. For example, the formation of zero-energy bound states at the surfaces of d_{xy}-wave superconductors is interpreted as one of the signature of the odd frequency pairing at the surface of anisotropic superconductors. Moreover, it is expected that the proximity effect due to odd frequency pairing states seriously affect the transport properties of SN and SNS systems when the superconductor has p-wave symmetry. This is because the proximity effect in the normal metal of this configuration is robust against the impurity scatterings. In order to detect the proximity due to odd frequency pairing, we have fabricated Sr_2RuO_4/Au/Sr_2RuO_4 structure as shown in Fig. 1. At present we were not succeeded in detecting the supercurrent between the two superconductors because of the degradation at the Sr_2RuO_4/Au boundary. Further improvements are in progress.

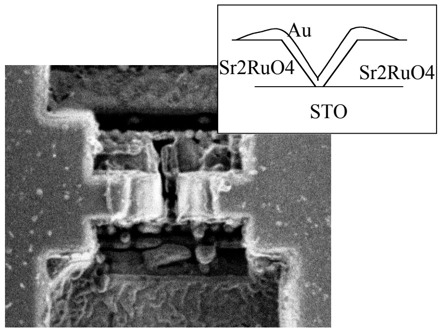

FIG.1: SIM image of Sr_2RuO_4/Au/Sr_2RuO_4 junction fabricated by FIB and sputtering methods.

STM/STS study of Sr_2RuO_4
- Search for an Anomalous Proximity Effect -

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Recently, Tanaka *et al*. predicted that enhanced proximity effect by the midgap Andreev resonant state (MARS) would appear in a diffusive normal-metal / triplet (DN/TS) superconductor junction [1]. The MARS can coexist with proximity effect for the DN/TS junctions, while the MARS compete with proximitiy effect for the DN/singlet superconductor junctions. Therefore, detecting the enhanced proximity effect can be a crucial test to identify spin-triplet superconductors. Sr_2RuO_4 is well-known as the p_x+ip_y-wave superconductor, and it is one of the most suitable candidates to detect the anomalously enhanced proximity effect. Specifically, the zero-bias density of states on the DN side is expected to *increae below* T_c of TS.

By using an ultra-low temperature STM (30 mK, 6 T, UHV), we are starting to search for this enhancement of the proximity effect. According to our previous STM/STS experiments for the surface of Sr_2RuO_4, it is not easy to detect superconducting gap structure on a cleaved surface along *ab*-plane (An STM-tip is oriented perpendicularly to the *ab*-plane), possibly because of the surface reconstruction. Therefore, we will make the tip approach parallel to the *ab*-plane whose surface is polished mechanically. In this workshop, we would like to report a preliminary result.

[1] Y. Tanaka, S. Kashiwaya, and T. Yokoyama, Phys. Rev. B **71** (2005) 094513.