Numerical study of unconventional superconductor / a quantum dot / unconventional superconductor junction

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Abstract

A numerical study on the Josephson current through a quantum dot has been done by means of the quantum Monte Carlo method. A dot attached to two gapless superconductors with d-wave pairing is considered to enhance the possible Kondo effect at low temperatures. The junction becomes a π junction caused by the Coulomb blockade in a temperature range depending on strengthen of the repulsion U on the dot. Our result on temperature dependence of the Josephson current shows that the magnitude of the Josephson current through the π junction is suppressed by decreasing the temperature even well above the Kondo temperature.

Key words: Josephson effect, quantum dot, unconventional superconductor, Coulomb blockade, Kondo effect

1. Introduction

Correlation effects in a Josephson system made by a quantum dot have some characteristic features.[1–3] Two major correlation effects, *i.e.* the Coulomb blockade and the Kondo effect, result in appearance of a π-junction[4,1] and a 0-junction[2], respectively. These effects are known to exist for a quantum dot attached with two unconventional superconductors, where the zero energy state modifies characteristics of the Josephson current.[3]

In this paper, we report a numerical study on the Josephson effect through a quantum dot. Our main purpose is to elucidate temperature dependence of the Josephson current by utilizing the quantum Monte Carlo method. The numerical result is compared with previous analytical approaches. The current through the π junction shows gradual decrease by reducing the temperature even well above the Kondo temperature.

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2. Method

We consider a dot between two superconducting electrodes on which the d-wave pairing is assumed. Below the energy scale is given by t. Temperature dependence of the superconducting gap $|\Delta(T)|$ is given by the BCS theory. A tunneling limit without direct tunneling between superconductors is considered. Two tunneling paths having a hopping matrix t' between the dot and an electrode are assumed. The geometry of the system is the same as the one utilized in a previous report, where the zero energy state does not appear.[7] The transparency of the junction is characterized by $\Gamma = \pi N(0)(t')^2$, where $N(0)$ is the local density of states of an electrode when $|\Delta(T)| = 0$.

We adopt the Hirsch-Fye algorithm,which has been generalized for a magnetic impurity problem in a superconductor.[5,6] The number of the Trotter slices is denoted by L. A current formula written by the temperature Green's function is utilized to obtain the DC Josephson current.[8]

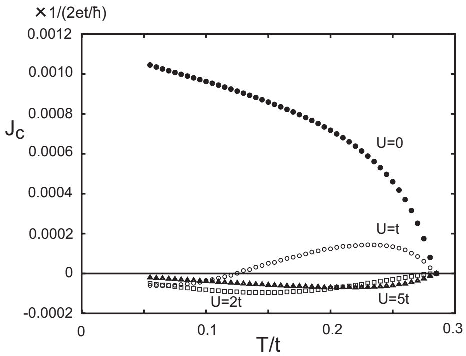

Fig. 1. Temperature dependence of the Josephson current J_c through a quantum dot. Closed circles, open circles, squares and triangles represent Josephson current for $U = 0$, t, $2t$ and $5t$, respectively. The transparency is $\Gamma = 0.079t$. When $J_c < 0$, the junction becomes a π-junction. For $U = t$, change in sign of the Josephson current occurs at $T \simeq 0.125t$.

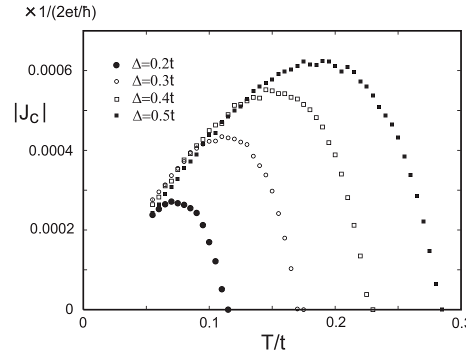

Fig. 2. Temperature dependence of the Josephson current through a quantum dot. Closed circles, open circles, squares and triangles are the current for $|\Delta(0)| = 0.2t$, $0.3t$, $0.4t$ and $0.5t$, respectively. Here $\Gamma = 0.39t$ and $U = 5t$.

3. Results

We first show typical result on the temperature dependence of the current in Fig. 1. The DC Josephson current J_c is obtained when a phase difference between two superconducting electrodes is $\pi/4$. Here both electrodes have $|\Delta(0)| = 0.5t$ and $\Gamma \sim 0.079t$. Thus the Kondo temperature T_0[6] is negligibly small. Here, data obtained using $L = 32$ is shown since L dependence has been confirmed to be small if $T \geq 0.05t$.

For finite U, the junction becomes a π junction. We see that the magnitude of the Josephson current decreases by reducing the temperature if $U = 2t$ or $U = 5t$. But our data is not necessarily inconsistent with previous result for much lower temperatures.[3]

To see how the Kondo effect affects the temperature dependence of J_c in this temperature range, we changed $\Delta(0)$ for a much transparent junction with $\Gamma = 0.39t$. (Fig. 2) When $U = 5t$ and $|\Delta(0)| = 0$, $T_0 \simeq 0.0076t$. In the spectral function at the dot, the Kondo resonance peak is found for $|\Delta(0)| = 0.2t$ and $0.3t$ but no resonance is seen for $|\Delta(0)| = 0.4t$ and $0.5t$. Obtained current shows however reduction of J_c irrespective of $\Delta(0)$ at lower temperatures. Since the Kondo effect is suppressed for large $\Delta(0)$, this result suggests that the suppression of the Josephson current may not be due to the Kondo screening but merely to large U.

4. Summary and Discussion

We have shown numerical data of the Josephson current through a quantum dot. Although our result is for a temperature range above the Kondo temperature, the magnitude of the Josephson current through the π junction is suppressed by decreasing the temperature if U is relatively large. Further investigation in lower temperatures is required to see the whole nature of the Josephson effect in this system. Since our approach can include detailed structures at the contact point, interplay of effects of the zero-energy state[9,3] and the electron correlation may be reinvestigated.

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References

[1] A.V. Rozhkov and D.P. Arovas, *Phys. Rev. Lett.* **82**, 2788 (1999).

[2] A.A. Clerk and V. Ambegaokar, *Phys. Rev. B* **61**, 9109 (2000).

[3] Y. Avishai and A. Golub, *Phys. Rev. B* **61**, 11293 (2000).

[4] B.I. Spivak and S.A. Kivelson, *Phys. Rev. B* **43**, 3740 (1991).

[5] M. Jarrell, D.S. Sivia and B. Patton, *Phys. Rev. B* **42**, 4804 (1990).

[6] W. Chung and M. Jarrell, *Phys. Rev. Lett.* **77**, 3621 (1996).

[7] K. Kusakabe and Y. Tanaka, submitted to *Proceedings of Int. Sym. Meso. Super. Spintronics,* NTT Atsugi, 2002 World Scientific.

[8] K. Kusakabe and Y. Tanaka, *J. Phys. Chem. Solids* in press.

[9] S. Kashiwaya and Y. Tanaka, *Rep. Prog. Phys.* **63**, 1641 (2000). Y. Tanaka and S. Kashiwaya, *Phys. Rev. B* **53**, 11957 (1996). Y. Tanaka and S. Kashiwaya, *Phys. Rev. Lett.* **74**, 3451 (1995).