Anomalous Meissner effect in NS junction with spin-active interface

Takehito Yokoyama\textsuperscript{1}, Yukio Tanaka\textsuperscript{2}, and Naoto Nagaosa\textsuperscript{3,4}
\textsuperscript{1}Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan
\textsuperscript{2}Department of Applied Physics, Nagoya University, Nagoya, 464-8603, Japan
\textsuperscript{3}Department of Applied Physics, University of Tokyo, Tokyo 113-8656, Japan
\textsuperscript{4}Cross-Correlated Materials Research Group (CMRG) and Correlated Electron Research Group (CERG), ASI, RIKEN, WAKO 351-0198, Japan
(Dated: January 12, 2013)

We investigate Meissner effect in normal metal/superconductor junctions where the interface is spin-active. We find that orbital magnetic susceptibility of the normal metal shows highly nontrivial behaviors. In particular, the magnetic susceptibility depends on the temperature in an oscillatory fashion, accompanied by its sign change. Correspondingly, magnetic field and current density can spatially oscillate in the normal metal. The possible spontaneous formation of the current pattern is also discussed. These results are attributed to the generation of odd-frequency pairing due to the spin-active interface.

PACS numbers: 73.43.Nq, 72.25.De, 85.75.-d

Interface phenomena related to the superconductivity constitute a rich field of condensed matter physics. When superconductor is attached to normal metal, Cooper pairs penetrate into the normal metal which acquires superconducting correlation. This is called the proximity effect. As a result, for example, the normal metal has a gap in the density of states or shows Meissner effect\textsuperscript{1–5}. In most cases, when lowering temperature, the proximity effect and hence the Meissner response become stronger.

However, unexpected behavior of the proximity induced Meissner response has been reported: Mota et al. have uncovered a low-temperature anomaly in the magnetic response of cylindrical structures. At very low temperatures, the susceptibility shows a reentrant behavior and even has paramagnetic region\textsuperscript{6–12}. However, the origin of this phenomenon still remains unclear.

Recently, it has been clarified that in normal metal/superconductor junctions, if the interface is spin-active, induced superconducting pairing in the normal region can change its symmetry from even-frequency pairing to odd-frequency pairing\textsuperscript{13, 14}. Here, even- or odd-frequency means that Cooper pair wavefunction is even or odd with respect to Matsubara frequency (or imaginary time)\textsuperscript{15}. If proximity induced pairing symmetry changes, the associated Meissner effect will also change qualitatively. This is the problem we address in this paper.

In this paper, we study Meissner response in the normal metal attached to superconductor where the interface is spin-active. We find that orbital magnetic susceptibility of the normal metal shows quite complex dependence on junction parameters. In particular, the magnetic susceptibility depends on the temperature in an oscillatory fashion, accompanied by its sign change. We also show the behavior of magnetic field and current density. These can spatially oscillate in the normal metal. These results are attributed to the generation of odd-frequency pairing which stems from the spin-active interface.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{model.png}
\caption{(Color online) Schematic picture of the model. Left: arrow in the circle represents the direction of spin, which is rotated at the scattering by the spin-active interface. Right: structure of the spin-active interface at $x = L$.}
\end{figure}

We consider a junction consisting of a diffusive normal metal (DN) with a length $L$ and resistance $R_d$, and a superconductor. We schematically show the model in Fig. 1. The interface between the DN and the superconductor at $x = L$ has a resistance $R_b$ (or tunneling conductance $G_T$) and the surface at $x = 0$ is specular. A weak external magnetic field $H$ is applied in $z$-direction (perpendicular to the plane of left panel of Fig. 1). We consider spin-active interface at $x = L$ which is described by mixing conductances $G_\phi$ and $G_\chi$ which reflect the spin rotation upon reflection and transmission at the interface, respectively.\textsuperscript{16, 17} To evaluate $G_\phi$ and $G_\chi$, we model magnetic barrier (interface) region as a rectangular potential $V$ with the exchange field $h$ and the width $d$ as shown in the right panel of Fig. 1 following Ref.\textsuperscript{17}. Figure 2 shows mixing conductances (upper) $G_\phi/G_T$ and (lower) $G_\chi/G_T$ as functions of $k_Fd$ and $V/E_F$ with the Fermi wavevector of the DN $k_F$ and the Fermi energy $E_F$. Mixing conductances oscillate with these parameters and $G_\phi/G_T$ rapidly increases when approaching $V/E_F = 1$.

To study the Meissner response, we adopt the quasiclassical Green’s function theory. The normal and
The boundary conditions for \( A(x) \) are given by
\[
\frac{d}{dx} A(0) = H, \quad A(L) = 0,
\]
where we have neglected the penetration of magnetic fields into the superconductor by assuming a small penetration depth in superconductor.

Finally, we obtain the expression of the orbital magnetic susceptibility,
\[
-4\pi\chi = 1 + \frac{A(0)}{HL}.
\]

We set \( h/E_F = 0.01 \), \( R_d/R_b = 10 \) and \( 16\pi^2 N(E_F) D^2 = 1000 \). Below, \( \xi \) and \( T_C \) denote the superconducting coherence length and the transition temperature, respectively. In the following, we plot \(-4\pi\chi\) with its magnitude less than unity since \(|4\pi\chi| > 1\) state indicates an instability toward some ordering or sublinear dependence on magnetic field due to the breakdown of linear response theory. When \(-4\pi\chi > 1\), the permeability \( \mu = 1 + 4\pi\chi \) becomes negative and hence the energy density \( B^2/2\mu \) is unstable at \( B = 0 \). This suggests that the new ground state with spontaneous current and magnetic field distribution is stabilized. Also, correspondingly, plots of magnetic field and current density are restricted to a certain regime of magnitude.

Figure 8 shows susceptibility \(-4\pi\chi\) at \( L/\xi = 10 \) with (upper) \( V/E_F = 0.95 \) and (lower) \( V/E_F = 1 \). At \( V/E_F = 0.95 \), over some region, paramagnetic state, namely that with positive \( \chi \), appears. At \( V/E_F = 1 \), stronger oscillation of the susceptibility accompanied by its sign change is seen. When mixing conductance is present, odd-frequency pairing is generated in the DN region. This odd-frequency pairing makes it possible to oscillate magnetic field rather than suppress in the DN region, as explicitly shown below. Therefore, susceptibility could be positive when odd-frequency pairing correlation is dominant over even-frequency pairing in the DN.

If purely even (odd) frequency pairing state is realized in the DN, \( \theta_e \) becomes purely real (imaginary). Then, the sign of screening current Eq.\( \ref{eq:screening_current} \) depends on whether induced pairing in the DN is even- or odd-frequency pairing. This drastically changes the susceptibility. To understand this qualitatively, let us consider thin limit of DN where spatial dependence of \( \theta_e \) is negligible. Then, for purely even-frequency pairing state, the Maxwell equation reads
\[
\frac{d^2}{dx^2} A(x) = k^2 A(x),
\]
FIG. 3: (Color) Susceptibility $-4\pi \chi$ at $L/\xi = 10$. (upper) $V/E_F = 0.95$ and (lower) $V/E_F = 1$.

with a real constant $k$. Then, we have

$$A(0) = -\frac{H}{k} \tanh kL.$$  \hfill (9)

Upon insertion of this equation into Eq.(7), we find that $-4\pi \chi$ is positive definite. On the other hand, for purely odd-frequency pairing state, the Maxwell equation reads

$$\frac{d^2}{dx^2} A(x) = -\kappa^2 A(x)$$  \hfill (10)

with a real constant $\kappa$. Then, we obtain

$$A(0) = -\frac{H}{\kappa} \tan \kappa L.$$  \hfill (11)

Substituting this equation into Eq.(7), we find that $-4\pi \chi$ can change its sign. Moreover, it can show divergent behavior near $\kappa L = \pi/2 \mod \pi$. In this way, we can understand the behavior of the susceptibility in Figure 3. Positive sign of $\chi$ means that proximity induced superconductivity shows paramagnetism. It has been known that in $d$-wave superconductors, paramagnetic contribution to Meissner effect arises from the Andreev surface states.\cite{21,24} In stark contrast, paramagnetic Meissner effect predicted here does not require unconventional superconductivity.

Figure 4 shows susceptibility at $k_F d = 10$ with (upper) $V/E_F = 0.95$ and (lower) $V/E_F = 1$. The susceptibility oscillates with temperature while $L$ dependence is weaker. The inset shows susceptibility as a function of $T/T_C$ for $L/\xi = k_F d = 10$ and $V/E_F = 0.95$. Reflecting the presence of odd-frequency superconductivity, the susceptibility shows oscillating divergent behavior (The border between red and green regions in the main panel corresponds to the divergence of the susceptibility).

Figure 5 depicts normalized magnetic field $H(x)/H$ (upper) and current density (lower) at $L/\xi = k_F d = 10$ and $V/E_F = 0.95$. The current density $j(x)$ is plotted in the unit of $T_C L H/2 D$. For $T_C \sim 1$meV, $L \sim 1\mu$m, $H \sim 1$G and $D \sim 10^{-2}$m/s, $T_C L H/2 D \sim 10^9$A/m$^2$. As seen, both magnetic field and current oscillate in space. In a similar way to obtain Eq.(11), we can show that the oscillation is due to the odd-frequency pairing. Therefore, Figure 5 also indicates that odd-frequency pairing does not repel magnetic field. The relation between susceptibility and magnetic field can be obtained along the same line:

$$-4\pi \chi = 1 - \frac{\tan \kappa L}{\kappa L} = 1 - \frac{\sin \kappa L H(L)}{\kappa L H}.$$  \hfill (12)

This indicates that, to realize paramagnetic state, $H(L)$ has to be larger than $H$, namely, magnetic field at the interface should be larger than that at the surface of the DN.

To attain anomalous Meissner effect, dominant odd-frequency pairing in the DN is required. This can be
magnetic insulator such as EuO, EuS or La$_2$BaCuO$_5$ as a tunneling barrier. The possible spontaneous formation of the current pattern was also discussed. These results are attributed to the generation of odd-frequency pairing arising from the spin-active interface. Our results could be confirmed by experiments with $\mu$-SR or microwave resonance.

The authors thank D. J. Scalapino for useful discussion. This work is supported by Grant-in-Aid for Scientific Research (Grants No. 17071007, No. 17071005, No. 19048008, No. 19048015, No. 20654030, No. 22103005, No. 22340096 and No. 21244053) from the Ministry of Education, Culture, Sports, Science and Technology of Japan, Strategic International Cooperative Program (Joint Research Type) from Japan Science and Technology Agency, and Funding Program for World-Leading Innovative RD on Science and Technology (FIRST Program).

![FIG. 5: (Color) Magnetic field (upper) and current density (lower) at $L/\xi = k_F d = 10$ and $V/E_F = 0.95$. The plots are restricted to a certain regime of magnitude for clarity of figure.](image)

A. D. Zaikin, Solid State Commun. 41, 533 (1982).
O. Narikiyo and H. Fukuyama, J. Phys. Soc. Jpn. 58, 4557 (1989).
S. Higashitani and K. Nagai, J. Phys. Soc. Japan 64, 549 (1995).
W. Belzig, C. Bruder, and G. Schönh, Phys. Rev. B 53, 5727 (1996).
W. Belzig, C. Bruder, and A. L. Fauchère, Phys. Rev. B 58, 14531 (1998).
A. C. Mota, D. Marek, and J. C. Weber, Helv. Phys. Acta 55, 647 (1982).
P. Visani, A. C. Mota, and A. Pollini, Phys. Rev. Lett. 65, 1514 (1990).
A. C. Mota, P. Visani, A. Pollini, and K. Aupke, Physica B 197, 95 (1994).
F. Bernd Müller-Allinger and A. C. Mota, Phys. Rev. Lett. 84, 3161 (2000).
F. Bernd Müller-Allinger and A. C. Mota, Phys. Rev. B 62, R6120 (2000).
F. Bernd Müller-Allinger, A. C. Mota, and W. Belzig, Phys. Rev. B 59, 8887 (1999).
W. Belzig, C. Bruder, Yu. V. Nazarov, Journal of Low Temperature Physics 147, 441 (2007).
J. Linder, T. Yokoyama, A. Sudbo, and M. Eschrig, Phys. Rev. Lett. 102, 107008 (2009).
J. Linder, A. Sudbo, T. Yokoyama, R. Grein and M. Eschrig, Phys. Rev. B 81, 214504 (2010).
V. L. Berezinskii, JETP Lett. 20, 287 (1974).
D. Huertas-Hernando, Yu. V. Nazarov, and W. Belzig, Phys. Rev. Lett. 88, 047003 (2002).
A. Cottet, D. Huertas-Hernando, W. Belzig, and Y. V. Nazarov, Phys. Rev. B 80, 184511 (2009).
K. D. Usadel, Phys. Rev. Lett. 25, 507 (1970).
Y. Tanaka, Y. Asano, A. A. Golubov, and S. Kashiwaya, Phys. Rev. B 72, 140503(R) (2005).
T. Yokoyama, Y. Tanaka, and A. A. Golubov, Phys. Rev. B 75, 134510 (2007).
S. Higashitani, J. Phys. Soc. Jpn. 66, 2556 (1997).
H. Walter, W. Prusseit, R. Semerad, H. Kinder, W. Assmann, H. Huber, H. Burkhardt, D. Rainer, and J. A. Sauls, Phys. Rev. Lett. 80, 3598 (1998).
[23] Yu. S. Barash, M. S. Kalenkov, and J. Kurkijärvi, Phys. Rev. B 62 6665 (2000).

[24] The relation between Andreev surface states and odd-frequency pairing has been discussed in Y. Tanaka, A. A. Golubov, S. Kashiwaya, and M. Ueda, Phys. Rev. Lett. 99, 037005 (2007).

[25] J. Linder, T. Yokoyama, and A. Sudbo, Phys. Rev. B 77, 174514 (2008).

[26] D. Solenov, I. Martin, and D. Mozyrsky, Phys. Rev. B 79, 132502 (2009).

[27] H. Kusunose, Y. Fuseya, and K. Miyake, arXiv:1011.4712v1.