i-soliton, fractional flux and breakdown of time reversal symmetry in multi-band superconductor

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Abstract

We pointed out a soliton can be present in a multi-band superconductor [Phys. Rev. Lett. **88** (2002) 017002]. We named it i-soliton. It connects two different coherent states having different phases. Simultaneously the time reversal symmetry breaks down. The i-soliton traps a fractional flux inside a superconducting loop. These properties may realize a fractional flux quantum (FFQ) device without Josephson junction in a real space. It is beyond a single flux quantum(SFQ) decive. The i-soliton would be found in the multi-layer cuprate superconductor having crystallographically nonequivalent CuO_2 planes in one unit of which representative is $Cu_xBa_2Ca_3Cu_4O_y$ (Cu-1234).

Key words: $Cu_xBa_2Ca_3Cu_4O_y$ (Cu-1234); soliton; fractional flux; SFQ; time reversal symmetry

1. Introduction

Weakly coupled multiple superconducting order parameters are suggested in $Cu_xBa_2Ca_3Cu_4O_y$ (Cu-1234). [1–9] This multiple order parameters are thought to be present in bulk, which are different from multiplicity induced by the surface. [10,11] Its origin is the multiple band formed by the multiple CuO_2 plane in one unit cell. [12–14] In this paper we discuss an i-soliton in this multi-band superconductor.

2. Formulation

Gibbs free energy density in the two-band superconductor on a one dimensional case may be given as follows[15,16]

$$g(x) = \sum_{\nu=1,2} \alpha_\nu |\psi_\nu(x)|^2 + \sum_{\nu=1,2} \frac{\beta_\nu}{2} |\psi_\nu(x)|^4 + \sum_\nu \frac{\hbar^2}{2m_\mu} |\frac{\partial \psi_\nu}{\partial x}|^2 + \gamma(\psi_1^\dagger \psi_2 + \psi_2^\dagger \psi_1). \quad (1)$$

x is a coordinate. m_ν is mass of the pair. When the intra-band interaction is much larger than the inter-band interaction, the amplitude of the order parameter may tend to be kept constant by the intra-band interaction. In this situation the contribution of the relative phase between two order parameters may be separated.

$$g_\theta(x) = \sum_{\nu=1,2} \frac{\hbar^2 N_\nu}{2m_\nu} |\nabla_x \theta_\nu|^2 + 2\gamma\sqrt{N_1 N_2} cos(\theta_1 - \theta_2). (2)$$

N_ν and θ_ν are the density of the pair and its phase on the band indexed by ν. Minimizing the free energy, we obtained sine-Gordon equation. The sine-Gordon equation gives a soliton as a stable excited state which we call i-soliton.

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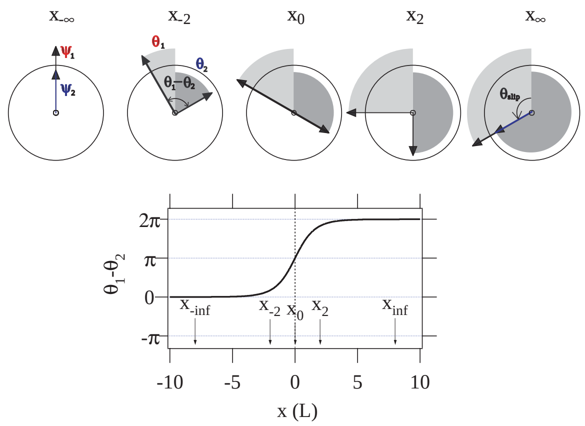

Fig. 1. (Top) Schematic diagram of the relative phase between two order parameter in several slices at location specified by x_i. (Bottom) Phase difference between two order parameters is depicted where $\frac{1}{m_0} = \frac{N_1 N_2}{m_1 N_2 + m_2 N_1}$ and $\frac{1}{L^2} = 4\frac{|\gamma|}{\hbar^2}\sqrt{N_1 N_2} m_0$.

3. Discussion

Figure 1 schematic description of the i-soliton. It connects two different superconducting ground states having different phase. [17,18] At an i-soliton, one order parameter rotates clockwise in the complex plain and another rotates counterclockwise. The i-soliton relates to a soliton observed in the extended Josephson junction composed of spatially separated superconductors. [19–21] The *inter-band Josephson coupling* assumes the role of extend Josephson junction in the i-soliton. The i-soliton is not accompanied by a flux and a real super current. The current in one band cancels that in other band. To catch the i-soliton, we should make a loop. The i-soliton is accompanied by the phase slip (Θ_{slip}). To compensate Θ_{slip}, the super current may be induced. The phase slip due to the i-soliton and the phase shift due to the super current give a total phase shift which should become $n\Phi_0$, where n is integer and Φ_0 is fluxoid quantum. Then the super current induce a fractional flux, which will be observed.

A single order parameter hardly allows a soliton. The phase slip at the soliton induces a supper current, but the pair brought by this current can not go anywhere and accumulates at the end of the soliton where the phase gradient vanishes. In case of the multi-band superconductor, the pair brought through one band can go back through another band. The i -soliton may be general phenomenon in the multi-band superconductor and it is not special one deduced by the restricted model we adopted in this report.

4. Conclusion

The multi-band superconductor has i-soliton. It will be observed.

References

[1] H. Ihara, K.Tokiwa, H. Ozawa, M. Hirabayashi, M. Matsuhata, A. Negishi and Y.S. Song, Jpn. J. Appl. Phys. **33** (1994) L300.

[2] H. Ihara, K.Tokiwa, H. Ozawa, M. Hirabayashi, A. Negishi, M. Matsuhata and Y.S. Song, Jpn. J. Appl. Phys. **33** (1994) L503.

[3] Y. Tanaka, A. Iyo, N. Shirakawa, M. Ariyama, M. Tokumoto, S. I. Ikeda and H. Ihara, Physica C **357-360** (2001) 222.

[4] Y. Tanaka, A. Iyo, N. Shirakawa, M. Ariyama, M. Tokumoto, S. I. Ikeda and H. Ihara, J. Phys. Soc. Jpn. **70** (2001) 329.

[5] Y. Tanaka, A. Iyo, H. Kato, K. Tokiwa, T. Watanabe and H. Ihara, Physica C in printing.

[6] Y. Tokunaga, K. Ishida, Y. Kitaoka, K. Asayama, K. Tokiwa, A. Iyo and H. Ihara, Phys. Rev. B **61** (2000) 9707.

[7] Y. Tokunaga, H. Kotegawa, K. Ishida, G. -q. Zheng, Y. Kitaoka, K. Tokiwa, A. Iyo and H. Ihara, J. Low. Temp. Phys. **117** (1999) 473.

[8] H. Kotegawa, Y. Tokunaga, K. Ishida, G. -q. Zheng, Y. Kitaoka, H. Kito, A. Iyo, K. Tokiwa, T. Watanabe and H. Ihara, Phys. Rev. B **64** (2001) 064515.

[9] A. Crisan, S. K. Agarwal, T. Koganezawa, R. Kuroda, K. Tokiwa, T. Watanabe, A. Iyo, Y. Tanaka and H. Ihara, J. Phys. Chem. Solid **63** (2002) 1073.

[10] K. Kuboki and M. Sigrist, J. Phys. Soc. Jpn.**65** (1996)361.

[11] M. Matsumoto and H. Shiba, J. Phys. Soc. Jpn.**64**(1995) 3384.

[12] K. Tokiwa, Y. Tanaka, A. Iyo, A. Tsubaki, K. Tanaka, J. Akimoto, Y. Oosawa, N. Terada, M. Hirabayashi, M. Tokumoto, S. K. Agarwal, T. Tsukamoto and H. Ihara, Physica C **298** (1998) 209.

[13] N. Hamada and H. Ihara, Physica B **284-288** (2000) 1073.

[14] J. Akimoto, K. Tokiwa, A. Iyo A, H. Ihara, H. Hayakawa, Y. Gotoh and Y. Oosawa, Physica C **279** (1997) 181.

[15] Y. Tanaka, J. Phys. Soc. Jpn. **70** (2001) 2844.

[16] Y. Tanaka, Phys. Rev. Lett. **88** (2002) 017002.

[17] P. C. Martin, *Superconductivity*, ed. R. D. Parks (Marcel Dekker,New York,1969) Vol. 2, Chap.7.

[18] R. B. Laughlin, Rev. Mod. Phys. **71** (1998) 863.

[19] K. Nakajima, Y. Onodera, T. Nakamura and R. Sato, J. Appl. Phys. **45** (1974) 4095.

[20] A. Fujimaki, K. Nakajima and Y. Sawada, Phys. Rev. Lett. **59** (1987) 2895.

[21] K. Nakajima, H. Mizusawa, Y. Sawada, H. Akoh and S. Takada, Phys. Rev. Lett. **65**(1990) 1667.