Results in Physics 3 (2013) 74–79

Contents lists available at SciVerse ScienceDirect

Results in Physics

journal homepage: www.journals.elsevier.com/results-in-physics

New attractive-force concept for Cooper pairs and theoretical evaluation of critical temperature and critical-current density in high-temperature superconductors

Shinichi Ishiguri *

Fukui National College of Technology, Geshi, Sabae, Fukui 916-8507, Japan

ARTICLE INFO

Article history:
Received 27 January 2013
Accepted 11 May 2013
Available online 18 May 2013

Keywords:
Attractive force concept
Lorentz force
Critical temperature
Critical current
Spin-energy gap
Anisotropic property of superconducting energy gap

ABSTRACT

We propose a new attractive interaction between pairs of holes that results in Cooper pairs and a linear temperature dependence of the spin-energy gap derived from Fermi statistics. This interaction is a Lorentz force between two moving holes with equal velocity. This force is analogous to the attractive electromagnetic force between parallel current-carrying leads; local currents exist at a CuO_2 surface. Combining the spin-energy gap and the proposed attractive force, we derive a critical temperature equation that gives the dependence of critical temperature on doping. This equation contains electric charge, coherence, Debye temperature, hole concentration, and forbidden band gap. It does not contain numerical or fitting parameters. By comparing the values obtained by this equation with experimental results, we find that the proposed theory agrees with the results for doping dependence. Furthermore, we use the spin-energy gap to obtain results for the temperature dependence of critical current density.

1. Introduction

Many groups have contributed to research on superconductivity. Initially, the main focus was on low-temperature superconductivity, and by this process, the famous BCS theory was developed. Although current research is primarily focused on high-temperature superconductivity, basic concepts such as Cooper pairs are still studied. Currently, the mechanism of high-temperature superconductivity is also investigated. Understanding this mechanism is important for condensed-matter physics and for applications of high-temperature superconductors, such as superconducting magnets, motors, and magnetic-field separation.

Discussions in the literature primarily pertain to transitions with respect to temperature, magnetic field, and current (i.e., critical quantities) [1–3]. Quantum-flux dynamics is currently being discussed in relation to critical current and magnetic fields, although reference [4] presents a different viewpoint.

A major feature of high-temperature superconductors is a force that contributes to combining electron pairs. One of the considerations is that, experimentally, this force seems to depend on carrier concentration. Currently, two approaches are employed: the high-doping Fermi-liquid approach [1,3] and the resonating valence bond (RVB) model [5] in low-doping regimes.

In addition, the spin-energy gap affects the physics of these systems. Many theoretical and empirical studies imply that this energy gap is profoundly related to the mechanism of high-temperature superconductivity [6].

In this study, we introduce the spin-energy gap via Fermi statistics. We derive the critical temperature doping dependence and compare it with experimental results. We employ a model that differs from the Fermi-liquid and RVB models. By employing this technique, we can obtain the temperature dependence of critical current density and compare it with experimental results. The significant contribution of this paper is that it describes high-temperature superconductors using only a simple supposition.

First, we derive the temperature dependence of the spin-energy gap. This is related to the fact that Cooper pairs are iteratively destroyed and created at non-zero temperatures (i.e., the Fermi energy of holes is proportional to the spin-energy gap).

Next, we introduce the concept of a creation force for a Cooper pair. We discuss this in terms of an attractive force acting between a pair of parallel current-carrying leads (i.e., an electromagnetic force). We then assume that the two current-carrying leads are shortened to the wavelength of holes, which shows us that two holes with the same velocity experience an attractive Lorentz force between each other. Based on this concept, the superconducting

* Tel.: +81 778 62 8263.
E-mail addresses: ishiguri@fukui-nct.ac.jp, kckyg592@ybb.ne.jp

2211-3797 © 2013 The Author. Published by Elsevier B.V. Open access under CC BY license.
http://dx.doi.org/10.1016/j.rinp.2013.05.002

energy gap is produced. Combining the spin-energy gap and this attractive force concept, we derive a critical temperature equation. This equation contains various parameters, such as coherence, hole concentration, the forbidden band gap E_G, and electric charge. By comparing the values obtained by the equation with experimental values, we find that this equation effectively predicts the dependence of critical temperature on carrier doping.

Finally, based on the derived spin-energy gap, we derive a temperature-dependent critical current equation. The results of this formula also agree with the experimental results.

2. Theory

2.1. Spin-energy gap derived from Fermi statistics

In this study, we consider a *p*-type material. At non-zero temperatures, electron pairs iteratively form and destroy Cooper pairs, which implies that the number of holes and the Fermi energy E_F vary. In *p*-type materials, larger E_F values result in fewer holes. Instead, the number of Cooper pairs increases. We assume that the energy gap $|\Delta|^2$ is proportional to both the Fermi energy and the critical temperature:

$$|\Delta|^2 = k_B T_c E_F, \tag{1}$$

where k_B and T_c denote the Boltzmann constant and the critical temperature, respectively. From Fermi statistics, the Fermi energy of *n*-type and *p*-type materials is

$$n: E_F = E_i + k_B T \log\left(\frac{2N_A}{n_i}\right), \tag{2-1}$$

$$p: E_F = E_i - k_B T \log\left(\frac{2N_A}{n_i}\right). \tag{2-2}$$

Because most high-temperature superconductors have hole carriers, we employ the *p*-type Fermi energy. Thus, Eq. (1) becomes

$$|\Delta|^2 = k_B T_c\left\{E_i - k_B T \log\left(\frac{2N_A}{n_i}\right)\right\}. \tag{3}$$

In the second term of this equation, two spin holes are considered, which explains the appearance of why the coefficient 2.

In Eq. (3), the energy E_i is defined as

$$2E_i = k_B T_c. \tag{4}$$

This energy is the superconducting energy gap. In this study, there are two energy gaps: one given by Eq. (1) and the other by Eq. (4). We refer to the energy gap of Eq. (1) as the spin-energy gap.

From Eq. (4), we derive the following:

$$|\Delta|^2 = k_B T_c E_i\left\{1 - k_B \frac{T}{E_i} \log\left(\frac{2N_A}{n_i}\right)\right\}, \tag{5}$$

$$|\Delta|^2 = \frac{1}{2}(k_B T_c)^2\left\{1 - 2\frac{T}{T_c} \log\left(\frac{2N_A}{n_i}\right)\right\}. \tag{6}$$

Furthermore, the equation of state

$$PV = 2N_A RT \tag{7}$$

is used, where P, V, N_A, R, and T denote the pressure, volume, hole concentration, universal gas constant, and temperature, respectively.

Thus, the spin-energy gap becomes

$$|\Delta|^2 = \frac{1}{2}(k_B T_c)^2\left\{1 - 2\frac{1}{T_c}\frac{PV}{R}\frac{1}{2N_A} \log\left(\frac{2N_A}{n_i}\right)\right\}, \tag{8-1}$$

$$|\Omega_B| = PV, \tag{8-2}$$

where Ω_B denotes the thermodynamic potential.

Thus, the spin-energy gap becomes

$$|\Delta|^2 = \frac{1}{2}(k_B T_c)^2\left\{1 - 2\frac{1}{T_c}\frac{|\Omega_B|}{R}\frac{1}{2N_A} \log\left(\frac{2N_A}{n_i}\right)\right\}, \tag{9}$$

2.2. Mechanism of attractive force and critical temperature

We consider two current-carrying leads that carry current in the same direction, as indicated in Fig. 2-1. According to classical electromagnetism, these leads exert an attractive force on each other, which stems from the Lorentz force. We now consider shortening these leads, as indicated in Fig. 2-2. Despite this shortening, the two leads still experience the attractive force; therefore, we assume that, even when the length of the leads approaches the wavelength of a carrier (i.e., a hole), the leads (i.e., the two holes) experience the same attractive force, as indicated in Fig. 2-3.

Therefore, two holes that move at equal velocity exert an attractive force on each other, which implies that these holes form a Cooper pair, as indicated in Fig. 2-4. This implies that a local cur-

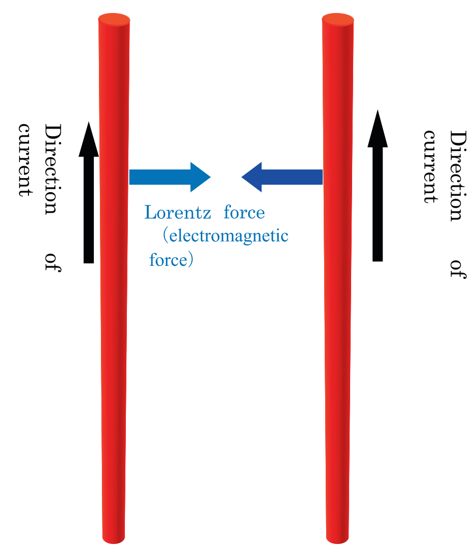

Fig. 2-1. Currents in same direction.

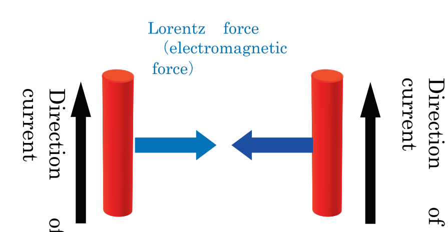

Fig. 2-2. Shorter leads with currents in same direction.

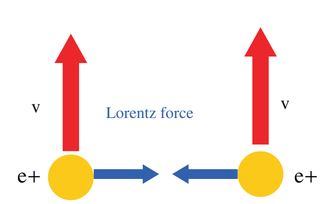

Fig. 2-3. Holes with same direction and equal velocity.