Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Correlation among the effective mass (m^*), λ_{ab} and T_c of superconducting cuprates in a Casimir energy scenario

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ARTICLE INFO

Article history:
Received 2 February 2018
Received in revised form 29 March 2018
Accepted 1 April 2018
Available online xxxx
Communicated by R. Wu

Keywords:
Casimir effect
Superconductivity
Condensate energy

ABSTRACT

The relevance of the Casimir effect, discovered in 1948, has recently been pointed out in studies on materials such as graphene and high-temperature superconducting cuprates. In particular, the relationship between Casimir energy and the energy of a superconducting condensate with anisotropy characterized by high bidimensionality has already been discussed in certain theoretical scenarios. Using this proposal, this work describes the relationship between the effective mass of the charge carriers ($m^* = \alpha m_e$) and the macroscopic parameters characteristic of several families of high-T_c superconducting cuprates (Cu-HTSC) that have copper and oxygen superconducting planes (Cu-O). We have verified that an expression exists that correlates the effective mass, the London penetration length in the plane λ_{ab}, the critical temperature T_c and the distance d between the equivalent superconducting planes of Cu-HTSC. This study revealed that the intersection between the asymptotic behavior of α as a function of T_c and the line describing the optimal value of $\alpha \simeq 2$ ($m^* \simeq 2m_e$) indicates that a nonadiabatic region exists, which implies a carrier-lattice interaction and where the critical temperature can have its highest value in Cu-HTSC.

1. Introduction

The Casimir effect appears to be increasingly important in understanding the interactions in various areas of physics [1], especially in the development of new theoretical and computational methods. In 1948, Casimir [2] predicted the existence of an attractive force between two parallel and electrically neutral conductors, which can be interpreted as a change of the zero-point energy due to fluctuation of the electromagnetic waves. This effect was called the Casimir Effect. Several studies have since focused on its experimental verification [3–6]. Other works seek to establish new models for applications in different materials. Among them, we highlight the work of Bordag [7] who, in 2006, studied the effect of Casimir energy between two thin plasma plates, modeled by Barton [8]. The Bordag model [7] proposed that an interaction can occur for interplanar distances that are of the order of the plasmons wavelength.

In 2006, Bordag et al. [9] published one of the first studies of Casimir interactions for graphene, modeling it as a plasma sheet. Based on the Bordag model [7], Kempf [10] published an article about the Casimir effect on high-T_c superconducting cuprates (Cu-HTSC), also modeling them as plasma sheets. In this work, Kempf [10] described CuO_2 planes as plasma planes that interact through the forces of Casimir [2]. With this scenario, the Kempf [10] proposal relates T_c to the ratio between the number of charge carriers and their effective mass.

The high-temperature superconducting cuprates, discovered in 1986 [11], are schematically described as being formed by two structural components in their unit cell, namely: (1) a block that functions as a charge reservoir, whose general formula is $MBa_{2-x}O_{4-d}$, (with M = La, Y, Tl, Hg, Bi, $x = 0, 1, 2$) interspersed by (2) a set of n planes of CuO_2 (n = 1, 2, 3, 4, 5, 6) [12]. To date, the highest transition temperatures have been reported for the $HgBa_2Ca_2Cu_3O_{8+x}$ compound, which belongs to the family of mercury-based cuprates. This family, represented by Hg-12(n−1)n, had the highest $T_c (= 164$ K) under pressure for the compound with n = 3.

The literature review reveals that Putilin et al. [13] were the first to synthesize the $HgBa_2CuO_{4+d}$ (Hg-1201) compound, which showed $T_c = 94$ K. The family of Cu-HTSC with mercury (Hg) was synthesized by other groups successfully at the end of the last century [13–16]. Our group has been investigating the physical and chemical characteristics of the Hg-12(n − 1)n family since 1998 [17–19].

As described, the Kempf proposal, associated with Casimir energy and the Bordag proposition, correlates the ratio between the

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https://doi.org/10.1016/j.physleta.2018.04.001
0375-9601/

number of carriers and the effective mass at the transition temperature. In Cu-HTSC, the number of carriers is difficult to evaluate, since few direct measurements are performed in monocrystals, such as the thermopower or the Hall effect. In polycrystals, these measures are of little reliability. However, Uemura et al. [20–22], indicated there exist another way to obtaining the relation between the number of carriers and the effective mass. It was shown [21] that muon-spin-relaxation (μSR) experiments establish a direct method to measure λ (magnetic-field depth penetration) in type-II superconductors. Considering that in superconductors $1/\lambda^2$ (λ – London depth) is essentially determined by (n_s/m^*) superconducting carrier density divided by effective mass. Uemura et al. [20] were the first to indicated a universal correlation between T_c and (n_s/m^*).

In this work, we associate the Uemura et al. proposal [20] with the Kempf model [10], taken into account muon-spin relaxation measures in anisotropic superconductors ($\simeq$2D) provide a correlation between n_s/m^* and the London penetration length λ_{ab} (parallel to the Cu-O planes). Considering this procedure, it was possible to obtain an expression that describes the behavior of the effective mass in Cu-HTSC as a function of $\lambda_{ab}(0)$ and T_c. Using this expression, we also compare the data obtained from this new correlation with values found in the literature.

2. Relevant parameters of the Cu-HTSC

A striking feature of the Cu-HTSC superconductors is the presence of a layered anisotropic structure that characterizes a strong two-dimensional behavior of the carriers in the Cu-O planes. This has implications for the mechanisms of electric transport and superconductivity [23,24].

2.1. Effective mass

Another feature of the Cu-HTSC can be associated with the model proposed by Lawrence and Doniach [25], which describes a 2D–3D transition due to the Josephson tunneling coupling of the superconducting planes that occurs at temperatures close to T_c. This anisotropy (high mobility in planes and tunneling behavior between orthogonal planes), associated with the mobility of the superconducting charge carriers, allows to describe the effective mass in the tensor form. In Cu-HTSC, the effective mass can be fully characterized by two components: $m_a^* = m_b^* = m_{ab}^*$ e m_c^* [26], where we can write the anisotropy factor as $m_c^* = \beta m_{ab}^*$. The average effective mass m_{av}^* can be described as equal to $\left(m_{ab}^{*2} m_c^*\right)^{1/3}$, as per ref. [26]. This allows us to write the effective mass m of these cuprates as

$$m^* = m_{av}^* = \left(m_{ab}^{*2} m_c^*\right)^{\frac{1}{3}} = \beta^{\frac{1}{3}} m_{ab}^*. \tag{1}$$

The effective mass has been used in several medium-field models, especially in several studies on superconductor compounds conducted by Uemura et al. [20–22], who established a strong correlation between the critical temperature and the muon spin relaxation measure (μSR) in superconductors. A μSR is associated with the inhomogeneous width of the local magnetic fields in the vortex state under the action of a high external magnetic field. Using this information, Uemura [20–22] et al. proposed the correlation between the London penetration depth and the ratio between the number of carriers divided by the effective mass. The penetration depth λ of the magnetic field is a parameter of the superconductivity associated with the density of the carriers n and the effective mass m^* in the following way:

$$\lambda(0) = \sqrt{\frac{m^*}{\mu_0 n_{3\mathrm{D}} q^2}}, \tag{2}$$

where μ_0 is the magnetic permeability in vacuum, q is the charge of the carriers and n_{3D} is the volumetric density of carriers.

Some studies [27,28] indicate that, for large anisotropies, the effective penetration depth becomes independent of the real anisotropy, being exclusively determined by the depth of penetration in the plane, i.e., λ_{ab}. Thus, using Eq. (1) in Eq. (2) we have $\lambda(0) = \beta^{\frac{1}{6}} \lambda_{ab}(0)$. The density of volumetric carriers $n_{3\mathrm{D}}$ can be related to the density of planar carriers $n_{2\mathrm{D}}$ through the expression $n_{2\mathrm{D}} = n_{3\mathrm{D}} d$ [29]. Therefore, the relationship between $\lambda_{ab}(0)$ and m_{ab}, analogous to Eq. (2) is

$$\frac{\lambda_{ab}(0)}{d^{\frac{1}{2}}} = \sqrt{\frac{m_{ab}^*}{\mu_0 n_{2\mathrm{D}} q^2}}. \tag{3}$$

2.2. 2D condensing energy of the superconducting state

Considering that Bordag's proposal [7] treats the surface plasmons as a dominant mechanism associated with the Casimir force in small separations, understanding the 2D density state is necessary. Therefore, for the surface, the calculation of the density of states can be performed considering the Fermi energy in two dimensions [30], which can be described as

$$D(E_f) = \frac{m^* A}{\pi \hbar^2}. \tag{4}$$

Considering that $\Delta(0) = \eta k_B T$ is the superconducting gap energy [31], the condensing energy for the superconducting state is

$$E_{\mathrm{cond}} = \frac{1}{2} D(E_f) \Delta^2(0). \tag{5}$$

As a consequence, the superconducting condensation energy can be rewritten as

$$E_{\mathrm{cond}} = -\frac{m^* A \eta^2 k_B^2 T_c^2}{2\pi \hbar^2}. \tag{6}$$

3. Casimir energy associated with thin plasma plates configuration

The Casimir effect occurs between two perfectly parallel and neutral conductive plates separated by a small distance compared to each area, $d \ll A$. In this configuration, the energy associated is

$$E_{\mathrm{cas}} = -\frac{\hbar c \pi^2 A}{720 d^3}, \tag{7}$$

where $\hbar$ is the Planck constant divided by 2π, c is the speed of light in vacuum, A is the area of the plates and d is the distance between the plates [2].

Bordag [7] proposed that between thin plasma plates, the Casimir energy is dominated by surface plasmons (that is, propagation waves along the surface) that define the Casimir force in small separations (nanometer scale). However, in large separations, the photons (waves of propagation perpendicular to the surfaces) dominate the process. Based on this model, we can describe the Casimir energy through a transverse magnetic (TM) wave [7] given by

$$E_{\mathrm{cas}} \simeq -5 \times 10^{-3} \frac{\hbar c A}{d^{\frac{5}{2}}} \sqrt{\Omega}, \tag{8}$$