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Estimation of Anisotropic Coherence Length in High-T_c Superconductors Using a Paraconductivity Approach

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Abstract

A comprehensive theoretical framework is developed to evaluate the anisotropic coherence length in high-temperature superconductors based on the fluctuation-induced conductivity approach. The theoretical model is formulated using well-established expressions derived from the anisotropic Ginzburg-Landau theory, incorporating both Aslamazov-Larkin and Maki-Thompson contributions. Numerical calculations are carried out for two representative superconducting systems, namely nano-$(Co_{0.5}Zn_{0.5}Fe_2O_4)_x$/(Cu,Tl)-1223 and Cd-doped (Cu,Tl)-1234 phase, which exhibit distinct dimensional characteristics. The reduced paraconductivity is analyzed as a function of reduced temperature, and the extracted parameters are compared with previously reported experimental data. The results demonstrate a good agreement between theoretical predictions and experimental observations, confirming the validity and applicability of the proposed model. Furthermore, the analysis highlights the strong influence of dimensionality and interlayer coupling on the anisotropic coherence length. The proposed approach provides a simple and reliable method for estimating superconducting parameters, which can be useful for both fundamental studies and technological applications of high-T_c superconductors.

Article Info.

Keywords:
High-Temperature Superconductor, Anisotropic Coherence Length, Paraconductivity, Ginzburg–Landau Theory, Fluctuation Conductivity.

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1. Introduction

The coherence length (denoted by ξ) is a fundamental parameter in understanding superconductivity. It indicates the distance over which a Cooper pair remains correlated in a superconductor or indicates the characteristic length scale of variation of the superconducting order parameter. In anisotropic or layered superconductors, the coherence length (so-called anisotropic coherence length) depends on the crystallographic directions due to anisotropic electronic structure and pairing interactions [1, 2], and becomes direction dependent, typically described by ξ_{ab} (in-plane) and ξ_c (out-of-plane), with their ratio $\gamma = \xi_{ab}/\xi_c$ giving a measurement of the anisotropy. This property influences other superconducting properties, e.g., the upper critical field, vortex behavior, and the dimensionality of superconducting fluctuations near T_c [3].

There are many experimental studies that have observed anisotropic coherence lengths in unconventional as well as novel superconductors. Talantsev [1] conducted a detailed analysis of coherence length anisotropy in infinite-layer nickelate and iron-based superconductors. The results revealed that the extracted superconducting thickness frequently exceeds the actual physical thickness of the films, indicating that both the in-plane and out-of-plane coherence lengths are larger than the film thickness. This behavior suggests an intermediate dimensionality and clear anisotropy in the superconducting properties. Arnault et al. [4] found an in-plane coherence length (~33 nm) and a critical field anisotropy (~20), which indicates extremely anisotropic behavior.

Determining ξ is essential for both fundamental research in superconductivity and for practical design applications [5, 6]. Recent experimental studies using advanced measurement techniques (e.g., stiffnessometry in zero applied field) have refined estimates of ξ, often revealing longer coherence lengths or modified temperature dependence compared to earlier assumptions, which in turn impacts theoretical modeling of pairing mechanisms and fluctuation effects [7]. In high-T_c and other unconventional superconductors, anisotropic coherence length makes the superconducting state much more sensitive to defects, disorder and grain boundaries, which reduces the number of overlapping Cooper pairs per coherence volume [8].

2. Theoretical Model

Fluctuation contribution, especially in electrical conductivity, may be attributed to three main effects: (i) a direct effect- formation of Cooper pair above T_c due to thermal fluctuation. Such direct contribution to the fluctuation conductivity was first investigated by Aslamazov and Larkin [9], also called the Aslamazov-Larkin (A-L) contribution; (ii) a redistribution of the electron density above T_c, which causes a decrease in the one-electron states at the Fermi level. A decrease in the one-electron density of states at the Fermi level reduces the normal-state conductivity. This indirect contribution to the Fluctuation Conductivity (FC) is called the Density Of States (DOS) contribution, which is very small in comparison with the A-L contribution and may be neglected, but sometimes it becomes very significant [10]; and (iii) an indirect effect, formation of Cooper pair (through coherent elastic scattering of electrons) due to the indirect acceleration of the fluctuating Cooper pairs introduced by Maki and Thompson (M-T) [11]. This additional conductivity is extremely sensitive to the pair-breaking interaction.

The original theoretical idea starts from the anisotropic Ginzburg-Landau (G-L) equation based on the fluctuation-dissipation theorem. For convenience, we started from the derived expression of the mentioned problem. Following Aslamazov and Larkin(A-L), Hopfengärtner et al. [12] obtained the expression for the excess-dc-conductivity tensor of anisotropic high-temperature superconductors, Eq. (1):

$$\Delta\sigma_{\alpha\beta}(T) = \frac{e^2\pi\xi_\alpha^2(0)\xi_\beta^2(0)}{\hbar V\varepsilon^3(T)}\sum_K \frac{K_\alpha K_\beta}{\left[1+\xi_x^2(T)K_x^2+\xi_y^2(T)K_y^2+\xi_z^2(T)K_z^2\right]^3} \tag{1}$$

Here, $\xi_{\alpha,\beta}(T)$ denotes the anisotropic coherence length $(\alpha, \beta = x, y, z)$, and V is the sample volume.

For anisotropic superconductors, applying an external electric field E along the x-direction and carrying out of the summation over all vectors K:

$\sum_K \quad \rightarrow \int \frac{d^3K}{(2\pi)^3}$, for bulk (3-D) materials

$\rightarrow \frac{1}{d}\int \frac{d^2K}{(2\pi)^2}$, for thin film $[d << \xi]$ or (2-D) system

$\rightarrow \frac{1}{S}\int \frac{dK}{2\pi}$, for a filament or (1-D) system

Eq. (2) can be derived [12]:

$$\Delta\sigma_{xx}^{3D}(T) = \frac{e^2\xi_x(0)}{32\hbar\xi_y(0)\xi_z(0)}\varepsilon^{-1/2} \tag{2}$$

$$\Delta\sigma_{xx}^{2D}(T) = \frac{e^2\xi_x(0)}{16\hbar d\xi_y(0)}\varepsilon^{-1} \qquad [\text{where}, \xi_z(T) >> d] \tag{3}$$

For an anisotropic system, one can assume that $\xi_x(0) = \xi_y(0) \neq \xi_{xy}(0)$ [equivalence of in-plane coherence length for layered superconductor] and Eq. (2) and (3) become:

$$\Delta\sigma_{AL}^{3D}(T) = \frac{e^2}{32\hbar\xi_z(0)}\varepsilon^{-1/2} \tag{4}$$

$$\Delta\sigma_{AL}^{2D}(T) = \frac{e^2}{16\hbar d}\varepsilon^{-1} \tag{5}$$

where $\varepsilon = (T - T_c^{MF})/T_c^{MF}$ is known as the reduced temperature within the mean-field transition temperature, T_c^{MF}.

Maki and Thompson (M-T) [11] corrected the A-L theory by considering indirect effects for the decay of the superconducting pairs into quasi-particles, and vice-versa. The quasi-particle contribution to the fluctuation conductivity during the breaking and reformation of the Cooper pair is resolved by strong inelastic scattering and by pair- breaking interaction. Therefore, the total excess conductivity is written as the sum of the regular (so-called A-L contribution) and anomalous (or M-T contribution), i.e., Eq. (6):

$$\Delta\sigma = \Delta\sigma_r + \Delta\sigma_a \tag{6}$$

Maki and Thompson (M-T) [11] first calculated the anomalous fluctuation conductivity $\Delta\sigma_a$. The result for an anisotropic high-temperature superconductor is as follows Eq. (7):

$$\Delta\sigma_a^{MT} = \frac{e^2\xi_x}{8\hbar\xi_y\xi_z}\left[\varepsilon^{1/2} + \delta_0^{1/2}\right]^{-1} \tag{7}$$

For a two-dimensional system, the result is Eq. (8):

$$\Delta_{2D}^{MT} = \frac{e^2}{8\hbar d(\varepsilon-\delta_0)}\ln(\varepsilon/\delta_0) \tag{8}$$

where $\delta_0 = (T^{MT} - T_c^{R=0})/T_c^{R=0}$ is the reduced temperature shift induced by pair-breaking interactions by Maki and Thompson [11], δ_0 may in general vary with field and temperature.

For a layered superconductor using L-D theory, Maki and Thompson obtained Eq. (9):

$$\Delta\sigma_x^{MT} = \frac{e^2\xi_x}{4\hbar\xi_y s(\varepsilon-\delta)}\ln\left[\frac{\varepsilon^{1/2}+(\varepsilon+4K)^{1/2}}{\delta^{1/2}+(\delta+4K)^{1/2}}\right] \tag{9}$$

The M-T term for the layered superconductor was modified by Hikami and Larkin [13], which induced both A-L and M-T contributions, and is given as follows (in zero field), Eq. (10):

$$\Delta\sigma^{MT}(T) = \frac{e^2\xi_x}{8\hbar d\varepsilon(1-\alpha/\delta)}\ln\left[\frac{\delta\left(1+\alpha+\sqrt{1+2\alpha}\right)}{\alpha\left(1+\delta+\sqrt{1+2\delta}\right)}\right] \tag{10}$$

where $\delta = \left\{\left(16\xi_z^2(0)k_\beta T\tau_\phi\right)/(\pi d^2\hbar)\right\}$ is a pair-breaking parameter, d is the interlayer periodicity and τ_ϕ is the phase breaking time.

To proceed, the temperature dependence of excess conductivity $\Delta\sigma(T)$, which is defined within the Ginzburg-Landau (G-L) mean field approximation [14], is Eq. (11):

$$\Delta\sigma(T) = \sigma_m(T) - \sigma_n(T) \tag{11}$$

where $\sigma_m(T)[= 1/\rho_m(T)]$ represents the measured electrical conductivity and $\sigma_n(T)[= 1/\rho_n(T)]$ is the linear normal-state conductivity. The normal-state resistivity of the sample $\rho_n(T)$

(is obtained from the measured resistivity $\rho_m(T)$ at $T \geq 2T_c$ by applying the least square method to the Anderson and Zou relation [15], Eq. (12):

$$\rho_n(T) = \rho_0 + \alpha T \quad \textbf{(12)}$$

where, α and ρ_0 are constants; $\alpha = d\rho/dT$ is the temperature resistivity coefficient which determines the slope of the linear dependence, $\rho_n(T)$ and ρ_0 is the initial or residual resistivity (arising from the temperature-dependent scattering of electrons (charge carriers) by impurities, lattice defects (e.g. vacancies, dislocations), grain boundaries, and structural disorder within the material, rather than thermal vibrations) cut off by this line on the Y-axis at T=0 [16-19]. The linear term αT originates from electron-phonon scattering, which increases with temperature due to the growing phonon population.
Eq. (11) can be written in the reduced form:

$$Y(T) = \frac{\sigma_{room}}{\Delta\sigma(T)} \quad \textbf{(13)}$$

where the parameter $Y(T) = [\rho_{room}/\rho_m(T) - \rho_{room}/\rho_n(T)]^{-1}$ is called the reduced paraconductivity, which is a function of temperature only, and $\rho_{room}[= 1/\sigma_{room}]$ is the room-temperature resistivity at about 300K.
Substituting Eq. (5) into Eq. (13), we get:

$$Y_1(T) = \frac{\sigma_{room}}{[(e^2/16\hbar d)\varepsilon^{-1}]} = m_1(T - T_c^{MF}) \quad \textbf{(14)}$$

where,

$$m_1 = \frac{16\hbar d}{e^2 \rho_{room} T_c^{MF}} \quad \textbf{(14a)}$$

Again, using Eq. (4):

$$Y_2(T) = m_2(T - T_c^{MF}) \quad \textbf{(15)}$$

where

$$m_2 = \frac{32\hbar \xi_z(0)}{e^2 \rho_{room} (T_c^{MF})^{1/2}} \quad \textbf{(15a)}$$

Squaring both sides of Eq. (15):

$$Y_2^2(T) = m_3(T - T_c^{MF}) \quad \textbf{(16)}$$

$$m_3 = \left[\frac{32\hbar \xi_z(0)}{e^2 \rho_{room} (T_c^{MF})^{1/2}}\right]^2 \quad \textbf{(16a)}$$

It is noted that the function Y(T) and the square of Y(T) [for the two- and three-dimensions, respectively] are linearly temperature dependent. Above T_c^{MF} both of them increase rapidly as the temperature increases. The slopes of the straight lines [corresponding to Eqs. (15) and (16)] are equal, i.e., $m_1 \equiv m_3$, only when:

$$\xi_z(0) = \left[\frac{d\rho_{room} e^2}{64\hbar}\right]^{1/2} \quad \textbf{(17)}$$

Here, an interesting relation for the anisotropic coherence length $\xi_z(0)\ is\ p$ is presented. For the known values of d and ρ_{room}, the room-temperature resistivity, the value of $\xi_z(0)$ can be directly obtained from Eq. (17). The method discussed above is identical to the method used by Bhatia and Dhard [20] for determining the value of T_c^{MF}, the mean-field transition temperature.

Putting the value of ρ_{room} from Eq. (17) into Eq. (14), the paraconductivity expression can be written as:

$$\frac{\Delta\sigma(T)}{\sigma_{room}} = \left[\frac{2\xi_z(0)}{d}\right]^2 \varepsilon^{-1} \quad \textbf{(18)}$$

This is a new (slightly modified) expression for paraconductivity in two dimensions. This includes a new parameter $\xi_z(0)$, the out-of-plane coherence length in two dimensions for paraconductivity measurements.

Similarly, from Eq. (15), the paraconductivity expression was obtained for a three-dimensional system:

$$\frac{\Delta\sigma(T)}{\sigma_{room}} = \left[\frac{2\xi_z(0)}{d}\right] \varepsilon^{-1/2} \quad \textbf{(19)}$$

3. Numerical Results and Discussion

A simple method was introduced for determining the anisotropic coherence length for high-temperature superconductors using paraconductivity expressions. To estimate $\xi_z(0)$ as well as d, the numerical result of Eqs. (18) and (19) for two- and three-dimensional superconducting systems were included. The quantity $\Delta\sigma(T)/\sigma_{room}(\sigma_{room} = 1/\rho_{room})$, where ρ_{room} denotes the room-temperature resistivity, which is an experimental measure of the magnitude of the fluctuation conductivity.

For numerical analysis, the expressions (18) and (19) can be written in the convenient form:

$$\ln\frac{\Delta\sigma(T)}{\sigma_{room}} = \ln(\alpha_0) - \ln(\varepsilon), \quad \alpha_0 = [2\xi_z(0)/d]^2 \quad \textbf{(20)}$$

$$\ln\frac{\Delta\sigma(T)}{\sigma_{room}} = \ln(\beta_0) - \frac{1}{2}\ln(\varepsilon), \quad \beta_0 = [2\xi_z(0)/d] \quad \textbf{(21)}$$

The logarithmic plot of $\Delta\sigma(T)/\sigma_{room}$versus $\varepsilon[= (T - T_c^{MF})/T_c^{MF}]$ is the experimental measure of fluctuation conductivity or paraconductivity from which $\alpha_0 = [2\xi_z(0)/d]^2$and $\beta_0 = [2\xi_z(0)/d]$ were determined. Here, the parameters α_0 and β_0 represent the prefactor of the Aslamazov-Larkin (A-L) fluctuation conductivity in the anisotropic Ginzburg-Landau (G-L) framework. α_0 denotes the strength of interlayer coupling and determines the magnitude of paraconductivity near T_c. β_0 is not a new theoretical parameter but a regrouped material-dependent prefactor used for linear fitting and extraction of $\xi_z(0)$.

Table 1: Experimental parameters of $T_c, \xi_z(0), d, T\ ln\ \varepsilon_{exp}$for $(Co_{0.5}Zn_{0.5}Fe_2O_4)_x$/(Cu,Tl)-1223 [21] and $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{4-y}Cd_yO_{12-\delta}$ [22], with x, y = 0,0.

Sample	T_c (K)	d (Å)	$\xi_z(0)$ (Å)	T_{exp} (K)	$ln\ \varepsilon$
(Cu,Tl)-1223 (2D)	112.0	235.540	16.57	113.92 <T_{exp}< 131.13	-3.97 to -1.78
(Cu,Tl)-1234 (2D, 3D)	109.3	17.86	1.6504	118.40 <T_{exp}< 121.41 121.41 <T_{exp}< 143.49	-3.37 to -1.5 -4.75 to -3.37

Fig. 1 shows such a plot for the sample reported by Barakat et al. [21], where $\alpha_0 = 0.019$ w used corresponding to $\xi_z(0) = 16.57 \times 10^{-10}$m and $d = 235.54 \times 10^{-10}$m. Our numerical result was comparable with the experimental results of Barakat et al. [21] for $(Co_{0.5}Zn_{0.5}Fe_2O_4)_x$/(Cu,Tl)-1223. The theoretical and experimental data followed approximately linear behavior over the range $-3.97 < ln\,\varepsilon < -1.78$, indicating a power-law dependence between the reduced paraconductivity and the reduced temperature in this fluctuation regime. The theoretical results closely followed the trend of the experimental results, demonstrating good agreement between the theoretical and the observed data. Minor deviations at some points may arise from experimental uncertainties discussed later.

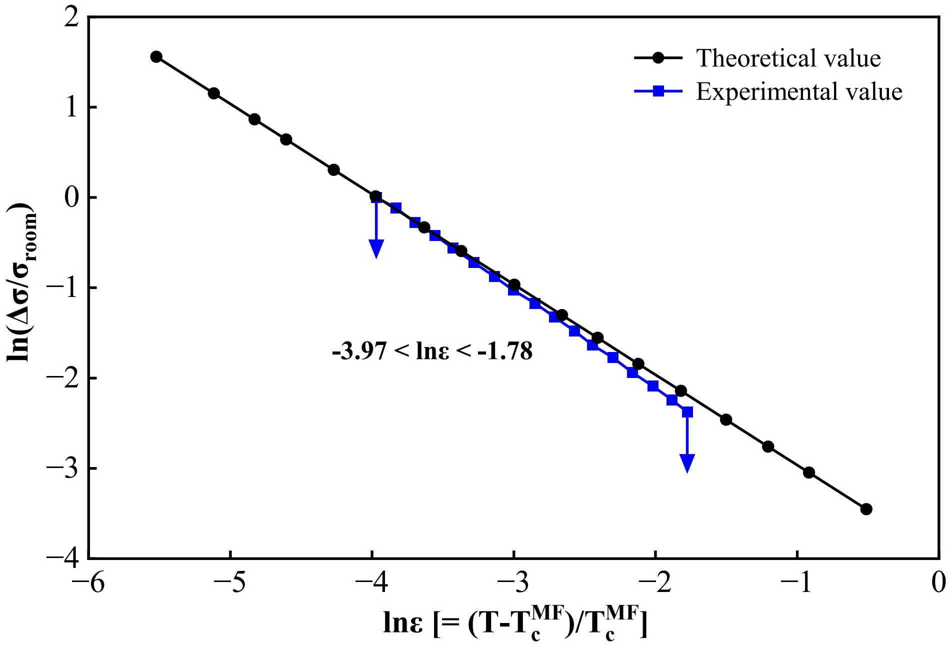

***Figure 1:** Log-log plots of the reduced paraconductivity versus reduced temperature for $(Co_{0.5}Zn_{0.5}Fe_2O_4)_x$/(Cu,Tl)-1223 with $x = 0.0$. The black-filled circle symbols represent the theoretical values [Eq. 20] and the square dots (blue color, marked by arrows) are the experimental data taken from Barakat et al. [21].*

Another experimental result was reported by Rahim and Khan [22] for the $(Cd)_y$/(Cu,Tl)-1234 phase, where the data were analyzed using the two-dimensional fluctuation conductivity model. Following their experimental parameters, the numerical calculation was performed using the corresponding values $\alpha_0 = 0.03416, \xi_z(0) = 1.6504 \times 10^{-10}$m and $d = 17.86 \times 10^{-10}$m. Our numerical results were comparable with the experimentally reported data [22], showing a linear behavior similar to that observed in Fig. 1.

For three-dimensional paraconductivity, the experimental result reported by Rahim and Khan [22] was reproduced for the same sample mentioned above, and can fit our data [within the temperature range indicated by the arrows in Fig. 3] to Eq. (21) by the substitution of $\beta_0 = 0.1848$. The theoretical curve closely followed the experimental data over the specified temperature range, indicating good agreement between the theoretical and the measured values. This agreement confirms that Eq. (21) clearly describes the three-dimensional paraconductivity behavior of the (Cu,Tl)-1234 superconducting phase within this temperature range.

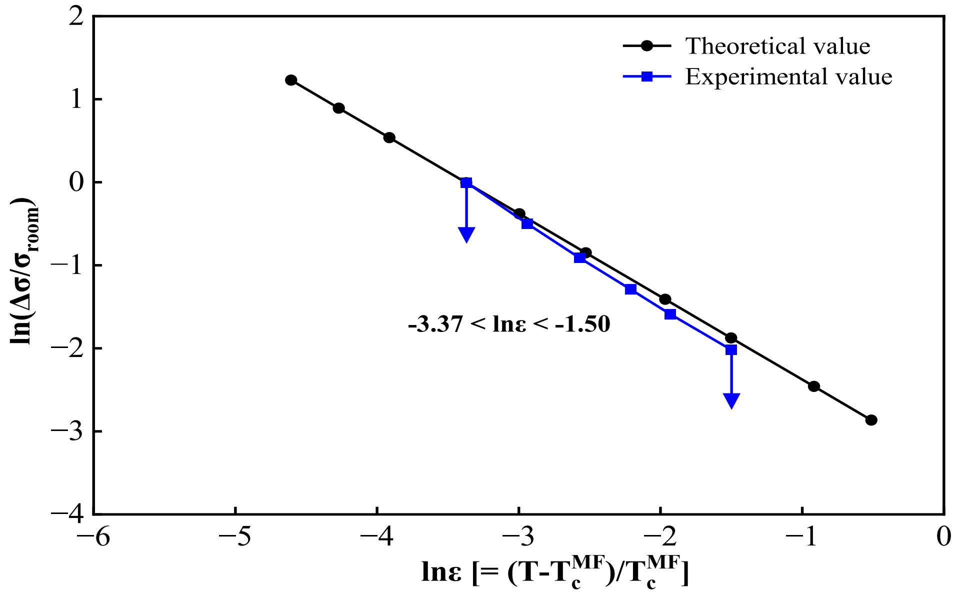

Figure 2: Logarithmic plots of $\Delta\sigma/\sigma_{room}$ versus $\varepsilon[=(T-T_c^{MF})/T_c^{MF}]$ for the sample $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{4-y}Cd_yO_{12-\delta}$ with $y = 0.0$. The black-filled circle symbols represent the theoretical values [Eq. 20] and the square dots (blue color, marked by arrows) are the experimental data taken from Rahim and Khan [22].

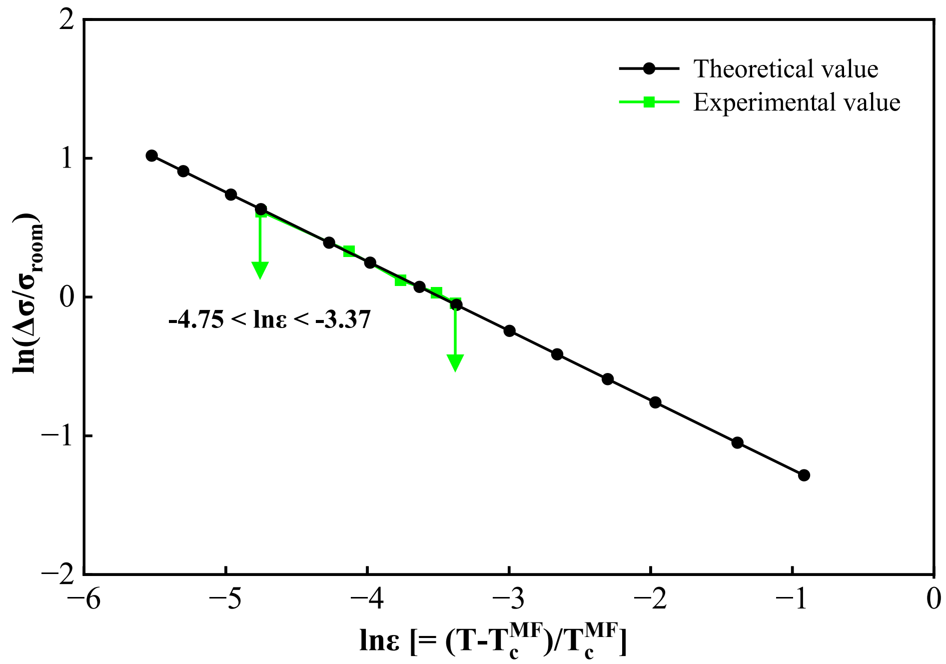

Figure 3: Same as in Fig. 2 for the same sample. The black-filled circle symbols represent the theoretical values [Eq. 21] and the square dots (green color, marked by arrows) are the experimental data taken Rahim and Khan [22].

4. Conclusions

In this work, a theoretical method was presented to evaluate the anisotropic coherence length in high-temperature superconductors using a fluctuation-enhanced conductivity or paraconductivity approach. Well-established paraconductivity formulations were applied to two representative systems: the $Co_{0.5}Zn_{0.5}Fe_2O_4$-doped (Cu,Tl)-1223 phase and the Cd-doped (Cu,Tl)-1234 phase, representing two- and three-dimensional structures, respectively. The analysis showed that two-dimensional superconductors exhibit greater anisotropy, while three-dimensional samples exhibit relatively lower anisotropy. To verify the theoretical results, previously reported parameter values for the selected compounds were employed. The data set was analyzed with the help of a statistical regression formula. The standard errors were: 0.38 for the (Cu,Tl)-1223 (2D) [see Fig. 1], 0.45 and 0.19 for (Cu,Tl)-1234 (2D, 3D) systems [see Figs. 2 and 3], respectively. This suggests that the experimental data used here are statistically reliable. In particular, the minimal deviation was observed for the 3D (Cu,Tl)-1234 sample compared to the 2D samples. The larger deviations observed in the 2D samples may originate from thier structural characteristics. For example, strong thermal fluctuations and weak interlayer coupling in low-dimensional superconductors can enhance fluctuation effects near the critical temperature, leading to larger discrepancies between the theoretical and experimental data. Although some deviations were observed, the results demonstrate good consistency between the theoretical and experimental findings, supporting the validity of the proposed model. The present study also highlights the importance of dimensionality in determining the fluctuation behavior and anisotropic properties of HTSC systems. Finally, it may be concluded that the paraconductivity approach is a useful tool for estimating the anisotropic coherence length in High Temperature Superconductors (HTSCs).

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Conflict of Interest

The authors declare that they have no conflict of interest.

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تقدير طول التماسك المتباين في الموصلات الفائقة ذات درجة الحرارة العالية باستخدام منهجية الموصلية المتوازية

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الخلاصة

تم تطوير إطارًا نظريًا شاملًا في هذا العمل لتقييم طول التماسك المتباين الخواص في الموصلات الفائقة ذات درجة الحرارة العالية، وذلك بالاعتماد على منهجية الموصلية المستحثة بالتقلبات. تمت صياغة النموذج النظري باستخدام تعابير راسخة مستمدة من نظرية جينزبورغ-لانداو المتباينة الخواص، مع دمج مساهمات كل من أسلامازوف-لاركين وماكي-تومسون. أجريت حسابات عددية لنظامين نموذجيين من الموصلات الفائقة، وهما: نانو-(Co0.5Zn0.5Fe2O4)x/(Cu,Tl)-1223 وطور (Cu,Tl)-1234 المُطعّم بالكادميوم، واللذان يتميزان بخصائص بُعدية متباينة. تم تحليل الموصلية المكافئة المختزلة كدالة لدرجة الحرارة المختزلة، وقورنت المعلمات المستخرجة بالبيانات التجريبية المنشورة سابقًا. أظهرت النتائج توافقًا جيدًا بين التنبؤات النظرية والملاحظات التجريبية، مما يؤكد صحة النموذج المقترح وقابليته للتطبيق. علاوة على ذلك، يُبرز التحليل التأثير الكبير للأبعاد والترابط بين الطبقات على طول التماسك غير المتناحي. يوفر النهج المقترح طريقة بسيطة وموثوقة لتقدير معلمات الموصلية الفائقة، والتي يمكن أن تكون مفيدة لكل من الدراسات الأساسية والتطبيقات التكنولوجية للموصلات الفائقة ذات درجة الحرارة العالية.

الكلمات المفتاحيه: موصل فائق ذو درجة حرارة عالية، طول تماسك متباين الخواص، موصلية شبهية، نظرية جينزبورغ-لاندا،موصلية التذبذب.