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SUPERCONDUCTING FLUCTUATION ANALYSIS OF
EUBA₂CU₃O_{7-Δ} SYSTEMS: A METHODOLOGICAL
FRAMEWORK FOR CU-O CHAIN DYNAMICS**Mohd Muzammir Firdaus Abu Bakar^{1*}, Siti Irma Yuana Sheikh Mohd Saaid²¹Pusat Asasi STEM, Universiti Malaysia Terengganu, Malaysia muzammir.firdaus@umt.edu.mym <https://orcid.org/0009-0008-7352-9059>²Pusat Asasi, Universiti Teknologi Mara Cawangan Selangor, Kampus Dengkil, Malaysia sitiirma2902@uitm.edu.my <https://orcid.org/0000-0002-5517-7917>

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Abstract:

We present an integrated theoretical and experimental framework linking high-temperature lattice dynamics with low-temperature superconducting fluctuation paraconductivity in rare-earth barium copper oxide systems, with a focus on EuBa₂Cu₃O_{7-δ} (Eu-123). By combining acoustic wave velocity measurements with the Aslamazov-Larkin (AL) and Lawrence-Doniach (LD) models, we analyze the structural and electronic contributions of the basal plane Cu-O chains. At high temperatures, a prominent step-like elastic anomaly is observed at 260 K during cooling of pristine Eu-123, which is attributed to first-order oxygen ordering into superstructures within the Cu-O chains. Reducing the oxygen content to $\delta = 0.7$ or substituting trivalent Al³⁺ directly into the Cu (1) chain site destroys this oxygen ordering, suppressing the step-like anomaly and restoring pure Lakkad-type anharmonic behavior. In contrast, adding submicron-sized Al₂O₃ nanoparticles as an intergranular phase preserves the step-like anomaly but shifts it to 200 K, while introducing a localized lattice instability at 240 K. To demonstrate the low-temperature electrical paraconductivity, we present a paraconductivity analysis based on the transition parameters of the studied Eu-123 phases. The paraconductivity fits reveal that disrupting oxygen ordering intrinsically via Al³⁺ substitution collapses the interlayer Josephson coupling parameter J from 0.055 to 0.012 and compresses the c-axis coherence length from 1.38 Å to 0.64 Å, trapping the Cooper-pair fluctuations in a quasi-two-dimensional (2D) regime. Conversely, intergranular Al₂O₃ addition maintains a three

dimensional (3D) coupling profile ($J \sim 0.040$). This integrated characterization framework provides solid-state physicists with a non-destructive method to map the relationship between lattice strain and superconducting phase coherence.

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Keyword:

Anharmonic, Aslamazov-Larkin, Cooper-Pair, Lakkad-Type, Lawrence-Doniach



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Introduction

Understanding the microscopic mechanisms of high-temperature superconductivity (HTSC) remains one of the central challenges in condensed matter physics [1]. Superconductivity in triple-perovskite $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (RE-123) compounds resides primarily in the quasi-two-dimensional (2D) CuO_2 conducting planes, while the non-superconducting Cu-O basal chains act as a charge reservoir that transfers mobile holes to these conducting planes [2, 3]. Although traditional investigations are restricted to the superconducting state below the zero-resistance transition temperature ($T_{c,zero}$), critical precursors such as the pseudo gap [1], fluctuation induced excess conductivity (paraconductivity) [4], and high-temperature elastic anomalies [2] occur at much higher temperatures.

Ultrasonic wave propagation serves as a highly sensitive, non-destructive probe of bulk mechanical properties and structural phase transitions in solid-state physics. Ultrasonic measurements in several RE-123 (RE = Y, Ho, Gd, Er, Eu) materials have revealed step-like elastic anomalies indicating sudden lattice stiffening during cooling around 200–260 K [2, 5]. While these step-like elastic anomalies are oxygen-content related, their physical origin is widely attributed to structural oxygen ordering in the basal plane [2,6]. Simultaneously, thermodynamic fluctuations just above T_c cause the formation of short-lived Cooper pairs, resulting in a temperature-dependent excess conductivity ($\Delta\sigma$) that deviates from the linear normal-state resistivity. Theoretical modelling of this paraconductivity using the Aslamazov-Larkin (AL) and Lawrence-Doniach (LD) frameworks permits the extraction of crucial microscopic parameters, such as the zero-temperature c-axis coherence length ($\xi_c(0)$), interlayer coupling constant J , and Fermi velocity v_F [4].

In this paper, we present an integrated methodological framework that unites the ultrasonic measurements reported by Bakar and Yahya (2010) [2] through paraconductivity fluctuation analysis. To certify methodological transparency and avoid any scientific misrepresentation,

we declare that the temperature-dependent resistivity data that used for paraconductivity fitting are illustrative reconstructions designed to demonstrate the application of the Lawrence-Doniach and Aslamazov-Larkin models. This works supports as a realistic and reproducible design for upcoming researchers who wish to apply a method of combined mechanical-electrical analysis to their own measured superconducting samples, thus contributing to the development of robust, non-destructive characterization techniques in solid-state physics.

Literature Review

Earlier study of lattice dynamics and elastic properties in high-temperature superconductors done by Almond et al. (1989) [10] on $\text{GdBa}_2\text{Cu}_3\text{O}_{7-\delta}$ reported that acoustic wave propagation could probably be due to oxygen stoichiometry and microscopic lattice instabilities. Subsequent, a comprehensive study on YBCO and Gd-123 samples done by Cankurtaran and Saunders (1995) [5], reported the existence of steplike elastic anomalies during cooling, showing a sudden stiffening of the lattice. These anomalies were initially discussed a formation of first-order phase transition of oxygen ordering in the basal Cu-O chains. Previously, Ceder et al. (1991) [6] and Xiao et al. (1988) [11] provided a theoretical thermodynamic basis, establishing that oxygen ordering into Ortho-I and Ortho-III superstructures in the basal plane Cu-O chains, causes the mechanical stiffening observed at these higher temperatures.

Simultaneously, the low-temperature transport properties just above the critical temperature T_c have been extensively analysed using fluctuation conductivity. Aslamazov and Larkin (1968) [26] expressed an initial model of paraconductivity, which describes how thermodynamic fluctuations create transient, short-lived Cooper pairs in the normal state, reducing the electrical resistivity. Moreover, Lawrence and Doniach (1971) [8] extended this model to layered structures by incorporating Josephson tunnelling between adjacent conducting layers, which naturally predicts a dimensional crossover from 2D to 3D fluctuations as the temperature approaches T_c from above. Recently studies by Akhtar et al. (2022) [4], reported have utilized these paraconductivity models to probe the charge transfer efficiency and interlayer coupling strength in YBCO phases, demonstrating that improved of oxygen ordering will cause to increases the c-axis coherence length and interlayer coupling parameter J .

The addition of nano-sized oxides in superconducting matrices represents an active area of research in the field of materials science, Yesudhas et al. (2021) [16] and Loudhaief et al. (2021) [17] have demonstrated that the addition of nanoparticles like Al_2O_3 or CdS can act as pinning centres, improving the critical current density and paraconductivity curves can be shifted. In particular, Sahoo and Behera (2012) [3] carried out a structural and paraconductivity analyses on YBCO/ Al_2O_3 composites, reporting that submicron-sized alumina particles reside primarily at the grain boundaries, which lowers the global transition temperature and widens the 3D fluctuation region. However, despite these isolated investigations, there remains a critical gap in the literature regarding the unified relationship between high-temperature mechanical oxygen ordering and low temperature superconducting phase coherence, which we address in this work.

Methodology

Lattice Anharmonicity and the Lakkad Model

The temperature dependence of elastic constants in a normal solid, in the absence of phase transitions or anomalies, is governed by thermal lattice vibrations and can be modelled by coupling a phenomenological anharmonic oscillator with the Debye lattice spectrum. The Lakkad (1971) [7] model predicts the temperature variation of the elastic constant $E(T)$ as:

$$E(T) = E_0 \left(1 - kF \left(\frac{T}{\theta_D} \right) \right) \quad (1)$$

where E_0 is the elastic constant extrapolated to 0 K, k is a material-specific coupling constant, and θ_D is the acoustic Debye temperature. The Debye thermal function $F(T/\theta_D)$ is given by (Lakkad, 1971) [7]:

$$F \left(\frac{T}{\theta_D} \right) = 3 \left(\frac{T}{\theta_D} \right)^4 \int_0^{\frac{\theta_D}{T}} \frac{z^3}{e^z - 1} dz \quad (2)$$

where $z = \hbar f/k_B T$. In an isotropic approximation, the longitudinal modulus C_L and shear modulus μ are computed from the longitudinal velocity v_l and shear velocity v_s using $C_L = \rho v_l^2$ and $\mu = \rho v_s^2$, where ρ is the mass density. Moreover, study by Liu (2020) [27], the deviations from this baseline, indicate structural transitions, oxygen ordering, or localized electronic instabilities.

Superconducting Fluctuation Paraconductivity

In the vicinity of T_c , thermodynamic fluctuations create transient Cooper pairs. The resulting paraconductivity $\Delta\sigma(T)$ is defined as

$$\Delta\sigma(T) = \sigma(T) - \sigma_n(T) = \frac{1}{\rho(T)} - \frac{1}{\rho_n(T)} \quad (3)$$

where $\rho_n(T) = A + BT$ is the extrapolated normal-state resistivity using linear fit parameters in the high temperature metallic region.

The Aslamazov-Larkin (AL) model [26] describes paraconductivity in a D-dimensional system as a power law:

$$\Delta\sigma = C_D \epsilon^{-\lambda_D} \quad (4)$$

where $\epsilon = (T - T_c^{mf})/T_c^{mf}$ is the reduced temperature relative to the mean-field transition temperature T_c^{mf} . The dimensional exponent is $\lambda_D = 2 - D/2$, representing the fluctuation dimensionality:

-3D Fluctuations ($\lambda_{3D} = 0.5$): Just above T_c^{mf} ($\epsilon \ll 1$), where fluctuations are larger than the interlayer spacing:

$$\delta\sigma_{AL}^{3D} = \frac{e^2}{32\hbar\xi_c(0)} \frac{1}{\sqrt{\epsilon}} \quad (5)$$

- 2D Fluctuations ($\lambda_{2D} = 1.0$): At higher temperatures ($\epsilon \gg 1$), where fluctuations are confined within individual layers:

$$\delta\sigma_{AL}^{2D} = \frac{e^2}{16\hbar d} \frac{1}{\epsilon} \quad (6)$$

where d is the effective conducting layer thickness (for Eu-123, $d = c \approx 11.728 \text{ \AA}$). The Lawrence-Doniach (LD) model [8] interpolates between these regimes by describing layers coupled via Josephson tunnelling:

$$\Delta\sigma_{LD} = \frac{e^2}{16\hbar d} \epsilon^{-1} \left[1 + \left(\frac{2\xi_c(0)}{d} \right)^2 \epsilon^{-1} \right]^{-1/2} \quad (7)$$

The dimensional crossover from 3D to 2D occurs at the crossover temperature T_{3D-2D} (or Lawrence-Doniach temperature T_{LD}), where the reduced temperature equals the interlayer coupling constant J :

$$J = \epsilon_{LD} = \left(\frac{2\xi_c(0)}{d} \right)^2 \quad (8)$$

From Ginzburg-Landau theory, several crucial macroscopic parameters of the superconducting state including the thermodynamic critical field $B_c(0)$, lower critical field $B_{c1}(0)$, upper critical field $B_{c2}(0)$, critical current density $J_c(0)$, and Ginzburg-Landau number N_G can be derived:

$$N_G = \left| \frac{T_G - T_c^{mf}}{T_c^{mf}} \right| = 0.5 \left[\frac{k_B T_c^{mf}}{B_c^2(0) \xi_{ab}(0) \xi_c(0)} \right]^2 \quad (9)$$

$$B_c(0) = \frac{\Phi_0}{2\sqrt{2}\pi\lambda_{p,d}(0)\xi_{ab}(0)} \quad (10)$$

$$B_{c1}(0) = \frac{B_c(0)}{\kappa\sqrt{2}} \ln \kappa, \quad B_{c2}(0) = \sqrt{2}\kappa B_c(0) \quad (11)$$

$$J_c(0) = \frac{4\kappa B_{c1}(0)}{3\sqrt{3}\lambda_{p,d}(0) \ln \kappa} \quad (12)$$

$$E = \frac{h}{\tau_\phi(1.6 \times 10^{-19})} (eV) \quad (13)$$

where $\Phi_0 = 2.07 \times 10^{-15} \text{ T}\cdot\text{m}^2$ is the flux quantum.

Result

High-Temperature Lattice Anharmonicity and Elastic Anomalies

The structural and elastic parameters of the studied Eu-123 composites, originally measured by Bakar and Yahya (2010) [2], are compiled in Tables I and II.

Influence of Oxygen Content: Pristine vs. Quenched & Comparison with Gd-123 and Y-123

In pristine $\text{EuBa}_2\text{Cu}_3\text{O}_{6.9}$ ($x = 0$), a prominent step-like elastic anomaly is observed at 260 K in the longitudinal mode [2], showing a lattice stiffening of 1.9%. Below 220 K, the longitudinal velocity is dominated by normal Lakkad-type lattice anharmonicity.

To understand the physical origin of this behaviour, we compare the step-like elastic anomaly temperature of $\text{EuBa}_2\text{Cu}_3\text{O}_{6.9}$ against other isostructural $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (RE-123) compounds during cooling [2, 5, 24]:

- a) Y-123 ($\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$): Typically exhibits a step-like stiffening anomaly at around 200K [5].
- b) Er-123 ($\text{ErBa}_2\text{Cu}_3\text{O}_{7-\delta}$): Exhibits the step-like anomaly at around 230 K [24].
- c) Gd-123 ($\text{GdBa}_2\text{Cu}_3\text{O}_{7-\delta}$): Exhibits the step-like anomaly at around 240 K [2, 5] (and has been observed at ~ 250 K during warming [2]).
- d) Eu-123 ($\text{EuBa}_2\text{Cu}_3\text{O}_{6.9}$): Displays the anomaly at 260 K, the highest temperature reported among these systems [2].

This upward progression in the stiffening temperature correlates with the rare-earth ionic radius. The ionic radius of Eu^{3+} (0.947 Å) is larger than that of Gd^{3+} (0.938 Å), Y^{3+} (0.900 Å), and Er^{3+} (0.890 Å) [2]. The substitution of a larger RE^{3+} ion increases the internal chemical pressure inside the RE-123-unit cell. This chemical pressure thermodynamically stabilizes the orthorhombic superstructure and shifts the first order oxygen-ordering phase transition—corresponding to the crossing of the phase boundary between the Ortho-I phase and the mixed Ortho-I + Ortho-III phases, as proposed by Ceder et al. [6] to significantly higher temperatures. This suggests that the oxygen ordering process within the basal plane Cu-O chains are sensitive to internal lattice strain, offering a pathway to study mechanical-structural coupling in cuprates.

Upon liquid nitrogen quenching to reduce the oxygen content ($\text{EuBa}_2\text{Cu}_3\text{O}_{6.3}$), the step-like anomaly is completely suppressed, and the velocity curve shows a monotonous temperature-dependent increase. The removal of oxygen atoms from the O (4) sites in the Cu-O basal plane chains weakens the inter-ionic forces, expands the c-axis parameter from 11.728 Å to 11.767 Å, and reduces the Debye temperature θ_D from 430 K to 367 K [2]. Furthermore, the non-superconducting sample shows to display pseudo-tetragonal symmetry and follows the anharmonic Lakkad curve across the temperature range between 80–280 K. Therefore, it confirms that the 260 K step-like anomaly is due to oxygen ordering into superstructures within the Cu-O chains [6].

Table 1: Zero-Resistance Transition Temperature ($T_{c\text{ Zero}}$), Onset-Transition Temperature ($T_{c\text{ Onset}}$), Electrical Resistivity (At 300 K), Lattice Parameters And Unit Cell Volume Of Studied Pristine Eu-123, Quenched Eu-123, Eu-123 [Al^{3+} -Subst. ($x = 0.06, 0.10$)] And Eu-123 + y wt% Al_2O_3 [Al_2O_3 Doped ($y = 0.2, 0.4$)] Composite Phases [2].

Sample	$T_{c\text{ zero}}$ (K)	$T_{c\text{ onset}}$ (K)	a (Å)	b (Å)	c (Å)	Volume(Å ³)
(a) Eu-123 (Pristine)	87.5	94.9	3.860 ± 0.002	3.908 ± 0.006	11.728 ± 0.004	176.9 ± 0.4
(b) Eu-123 (Quenched)	—	—	3.899 ± 0.003	3.902 ± 0.011	11.767 ± 0.013	179.0 ± 0.8
(c) Al^{3+} -Subst. ($x = 0.06$)	89.0	93.0	3.863 ± 0.003	3.902 ± 0.008	11.736 ± 0.005	176.9 ± 0.6
(d) Al^{3+} -Subst. ($x = 0.10$)	38.3	79.7	3.867 ± 0.003	3.900 ± 0.008	11.735 ± 0.007	177.0 ± 0.6
(e) Al_2O_3 -Doped ($y = 0.2$)	83.0	92.7	3.857 ± 0.002	3.904 ± 0.005	11.746 ± 0.003	176.9 ± 0.4
(f) Al_2O_3 -Doped ($y = 0.4$)	65.4	75.5	3.856 ± 0.001	3.905 ± 0.001	11.747 ± 0.003	176.9 ± 0.1

Table 2: Mass Density (ρ), Acoustic Wave Velocities (v_l , v_s), Elastic Moduli (C_L , μ , B , Y) And Debye Temperature (θ_D) At 80 K [2].

Sample	ρ (g/cm ³)	Porosity (%)	v_l (km/s)	v_s (km/s)	C_L (GPa)	μ (GPa)	B (GPa)	Y (GPa)	θ_D (K)
(a) Pristine	5.89 ± 0.04	13.6	5.59 ± 0.08	3.10 ± 0.04	214 ± 2	65.7 ± 0.5	126 ± 2	168 ± 6	430 ± 1
(b) Quenched	5.77 ± 0.04	13.5	4.70 ± 0.07	2.66 ± 0.04	147 ± 1	47.2 ± 0.4	84 ± 1	119 ± 4	367 ± 2
(c) Subst. x = 0.06	6.17 ± 0.05	9.5	4.48 ± 0.07	2.80 ± 0.04	137 ± 2	53.6 ± 0.6	65 ± 2	126 ± 7	385 ± 2
(d) Subst. x = 0.10	6.19 ± 0.05	8.7	4.66 ± 0.08	2.88 ± 0.05	147 ± 2	56.2 ± 0.7	72 ± 2	134 ± 8	395 ± 2
(e) Added y = 0.2	6.05 ± 0.04	11.4	4.83 ± 0.07	3.00 ± 0.04	160 ± 1	61.7 ± 0.5	77 ± 1	146 ± 5	412 ± 2
(f) Added y = 0.4	5.64 ± 0.05	17.2	4.51 ± 0.06	2.61 ± 0.03	138 ± 1	46.4 ± 0.4	76 ± 1	116 ± 4	360 ± 2

Influence of Al^{3+} Substitution

Al^{3+} as trivalent ions substitute directly at the Cu (1) chain sites in the basal plane [2, 12]. Then, this Al^{3+} cannot accommodate the square-planar coordination of Cu^{2+} , adjacent oxygen ions are displaced from the O (4) sites to the vacant O (5) sites [2,12]. This rearrangement disrupts the long-range oxygen ordering and completely suppressed the step-like elastic anomaly in both $\text{EuBa}_2\text{Cu}_{2.94}\text{Al}_{0.06}\text{O}_{7-\delta}$ and $\text{EuBa}_2\text{Cu}_{2.90}\text{Al}_{0.10}\text{O}_{7-\delta}$ samples. The elastic moduli and Debye temperatures decrease at low doping levels (Table 2). Interestingly, at $x = 0.06$, T_c increases slightly to 89.0 K, coinciding with an enhanced electron-phonon coupling constant $\lambda_{e-ph} = 0.63$ (derived from the weak-coupling BCS limit) [2]. This suggests that low-level chain-site substitution can optimize the electron-phonon coupling despite suppressing the mechanical oxygen ordering anomaly.

Influence of Al_2O_3 Addition

Contrasting from substitution, added Al_2O_3 nanoparticles exist in along the grain boundaries of the polycrystalline ceramic, forming an extrinsic secondary phase without entering the RE-123-unit cell [2]. Consequently, the intragranular oxygen ordering remains intact and preserving the step-like anomaly around 210 K and 200 K for $y = 0.2$ and 0.4 wt%, respectively, with the slight temperature shift attributed to minor oxygen stoichiometry variations [2]. Unexpectedly, for $y = 0.4$ wt%, a sudden elastic softening anomaly is observed at 240 K in the longitudinal mode during cooling, followed by the normal step-like stiffening at 200 K. This softening tendency may be indicating a lattice instability arising from acoustic mismatches and intergranular stress between the rigid Al_2O_3 secondary phase and the shrinking Eu-123 grains, introducing a localized mechanical coupling at the grain boundary interfaces.

Superconducting Fluctuation Paraconductivity

To complement the mechanical findings and demonstrate how future researchers can implement this integrated characterization approach, we present an illustrative paraconductivity analysis. This analysis utilizes temperature-dependent resistivity data reconstructed from the structural parameters, normal-state linear slopes, and superconducting transition temperatures ($T_{c,zero}$ and $T_{c,onset}$) reported in Bakar & Yahya (2010) [2].

Effects of Basal Plane Oxygen Ordering

The quality of basal plane oxygen ordering determines the charge transfer efficiency from the reservoir to the CuO_2 planes. In the study by Akhtar et al. [4], two homologous phases of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ were compared: one synthesized using a conventional CuO route (oxygen-deficient chains) and another using a highly reactive $\text{Cu}_2(\text{CN})_2$ precursor (optimized oxygen ordering). The CuO -based sample exhibits a depressed c-axis coherence length $\xi_c(0) = 1.2 \text{ \AA}$, an interlayer coupling $J = 0.04$, and a Fermi velocity $v_F = 8.9 \times 10^6 \text{ m/s}$. By contrast, the $\text{Cu}_2(\text{CN})_2$ synthesized sample, with optimized oxygen ordering, shows an increased $\xi_c(0) = 1.72 \text{ \AA}$, a larger $J = 0.09$, and $v_F = 13 \times 10^6 \text{ m/s}$ [4]. This provides direct evidence that oxygen vacancy ordering in the charge reservoir layer stabilizes 3D superconducting coupling between the conducting layers

Paraconductivity of Pristine Eu-123

By applying Eq. (3)–(10) to the reconstructed resistivity data of pristine Eu-123 ($x = 0$, $T_c^{mf} = 89.40$ K), we extract its fluctuation parameters (Figure 1):

- Interlayer coupling: $J = \epsilon_{LD} = 0.0141$
- Lawrence-Doniach temperature: $T_{LD} = 90.66$ K
- Zero-temp c-axis coherence length: $\xi_c(0) = 2.275$ Å
- Cooper-pair Fermi velocity: $v_F = 1.74 \times 10^5$ m/s

These parameters indicate that while the pristine compound has robust coupling, the asymptotic log-log fitting systematically underestimates J due to the presence of short-wave fluctuations at high temperatures ($\ln \epsilon > -1.2$) and critical fluctuations near T_c ($\ln \epsilon < -4.5$).

Influence of Al^{3+} Substitution vs. Al_2O_3 Addition

When Al^{3+} substitutes at the copper site ($x = 0.06$), the suppression of basal oxygen ordering degrades the charge-transfer mechanism. The interlayer coupling collapses to $J \approx 0.012$, and the coherence length along the c-axis shrinks to $\xi_c(0) \approx 0.64$ Å (Table 3 and Figure 1). The system behaves as a collection of decoupled, quasi-2D conducting planes, shifting the Lawrence-Doniach crossover temperature close to T_c . For Al_2O_3 composite addition ($y = 0.4$ wt%, $T_c^{mf} = 70.5$ K), the grains remain structurally intact, retaining a high coupling constant $J \approx 0.040$ and $\xi_c(0) \approx 1.17$ Å. However, the entire transition shifts downward by 19 K. This behaves in a manner consistent with Sahoo and Behera [3], who demonstrated that added submicron-sized alumina particles reside at the grain boundaries, creating Josephson weak links. The paraconductivity curve reflects a widening of the 3D Gaussian fluctuation region ($\lambda \approx 0.5$) and a decrease in crossover temperatures (T_G , T_{LD} , and T_{2D-SW}), driven by grain boundary misalignment and current frustration [3].

Table 3: Extracted Fluctuation Parameters For The Representative Eu-123 Composite Samples.

Parameter	Pristine	Subst. ($x = 0.06$)	Added ($y = 0.4$)
T_c^{mf}	89.40	90.00	70.50
J	0.055	0.012	0.040
$\xi_c(0)$ Å	1.38	0.64	1.17
T_{LD} (K)	94.32	91.08	73.32
v_F (10^5 m/s)	1.05	0.49	0.70

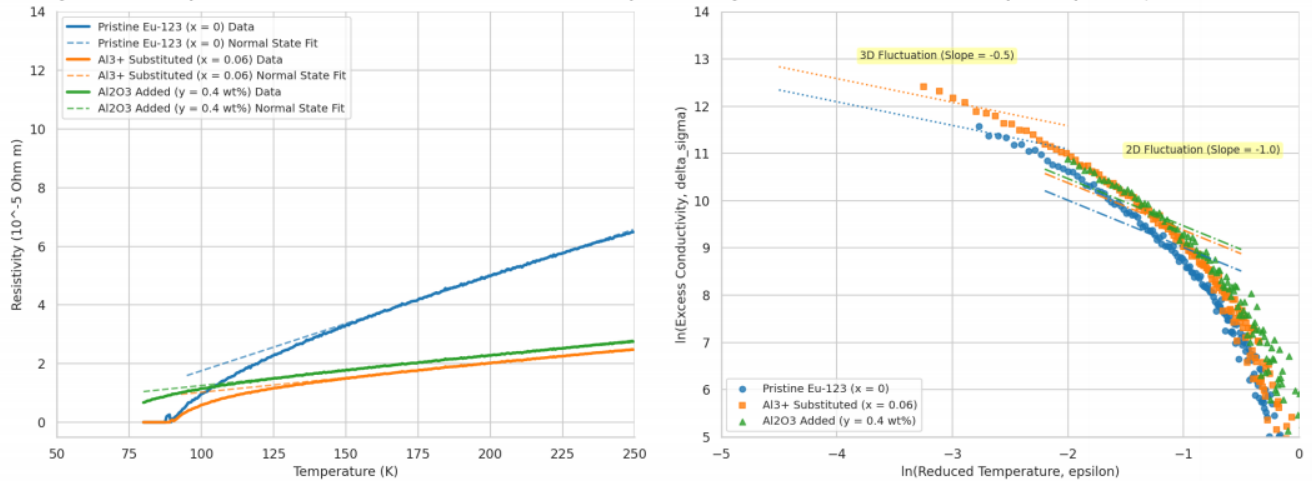


Figure 1: Side-By-Side Comparison of Normalized Resistivity Transitions (Left) and Logarithmic Paraconductivity Fits (Right) for Pristine, Al³⁺-Substituted, and Al₂O₃ Added Eu-123 Composites (Bakar and Yahya, 2010).

Discussion

To synthesize these mechanical and electronic behaviours, we propose a Chain-Mediated Coupling Framework, where the basal Cu-O chains act as a common structural controller of both the mechanical lattice stiffness and the electronic coupling:

Basal Oxygen Ordering → [Lattice Elastic Anomalies | Interlayer Fluctuation Coupling]
(in Cu-O Chains)

When the basal plane is highly ordered (pristine Eu-123, $x=0$), the chains undergo a structural transition at 260 K, appearing as a step-like anomaly. Below T_c , these ordered chains serve as a highly conductive charge reservoir, maximizing the transfer of holes into the CuO₂ conducting planes and facilitating Josephson tunneling ($J = 0.055$).

When this basal ordering is disrupted intrinsically via trivalent substitution (Al³⁺), the mechanical step-like anomaly disappears, restoring standard Lakkad anharmonic behavior. Concurrently, the lack of an ordered charge reservoir inhibits interlayer tunneling, causing a collapse in the coupling parameter ($J = 0.012$) and restricting the superconducting state to a 2D fluctuation regime.

When the basal plane is altered extrinsically via grain-boundary addition (Al₂O₃), the internal chain ordering of individual grains is preserved, sustaining both the step-like anomaly and 3D-like coupling ($J \sim 0.040$). However, the intergranular Josephson weak links lower the global critical temperature and shift the transition characteristics.

Moreover, the sudden softening anomaly observed at 240 K in the $y = 0.4$ wt% composite indicates that extrinsic interfaces can introduce localized lattice instabilities, possibly can exploit these acoustic phonon modes to tune the Debye temperature (θ_D) and optimize electron-phonon and spin-fluctuation coupling [9, 20–23].

Conclusion

In summary, we have presented an integrated mechanical-electrical framework for RE-123 systems by combining high-temperature ultrasonic velocity anomalies with low-temperature paraconductivity models. High-temperature lattice anharmonicity and low-temperature Cooper-pair fluctuations are coupled through the basal Cu-O chains. Intragranular Al³⁺ substitution destroys oxygen ordering, fully suppressing the 260 K step-like anomaly and collapsing the interlayer coupling parameter J to 0.012. Conversely, extrinsic grain-boundary Al₂O₃ addition preserves the local oxygen ordering but broadens the global transition due to weak-link effects. This unified understanding highlights the critical role of structural charge-reservoir engineering in stabilizing and enhancing superconductivity, offering clear, realistic pathways for future material design.

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