



On Signatures of Room-Temperature Superconductivity Emerging in Bi/Pb Multiphase Cuprates Fabricated by the Solar Technology

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Abstract: In this work, we experimentally investigate the possible coexistence of distinct 3D and 2D superconducting phases in high- T_c ceramic cuprates. In these materials, unconventional tightly bound polaronic Cooper pairs are expected to exhibit bosonic behavior and undergo condensation below characteristic critical temperatures, forming 3D and 2D Bose superfluid states within their respective regions. According to the theoretical model, the superconducting transition temperature associated with 2D regions can substantially exceed that of the bulk 3D phase and may, under suitable conditions, approach room temperature. Experimental signatures for possible room-temperature superconductivity is reported at grain boundaries, 3D/2D interfaces, and within multiplate structures of ceramic superconductors with the composition $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ (where $n = 2 - 30$). These materials were synthesized using a novel melt-processing technique employing concentrated solar energy in a large solar furnace in Parkent. The resulting samples exhibit bulk T_c values ranging from approximately 100 to 140 K, together with significantly higher-temperature superconducting-like features associated with the 3D-2D crossover regime. Remnant 2D superconductivity-like features are observed at temperatures of approximately 200-300 K, substantially above the bulk T_c . Possible signatures of the onset of room-temperature superconductivity include a sharp, step-like decrease in electrical resistance, a measurable partial Meissner effect near 300 K, and differences observed through comparative torque and resonant radio-frequency (RF) magnetometry measurements of samples prepared using conventional solid-state reaction and solar-energy-based synthesis methods.

Keywords: Bi/P cuprates, Three- and two-dimensional superconducting phases, Room-temperature superconductivity, physical properties

INTRODUCTION

Remarkable advances in condensed matter physics have frequently been driven by the discovery of new superconducting materials and superfluid systems, including both Fermi and Bose liquids. In particular, the discovery of La-based high- T_c cuprate superconductors [1-3], followed by the substantial increase in the critical temperature T_c to above 90 K [4], 110 K [5], and 130 K [6] in Y-, Bi-, and Hg-based cuprate superconductors, respectively,

ushered in a new era in both fundamental physics and technological development. These discoveries stimulated extensive efforts to identify new materials capable of exhibiting even higher superconducting transition temperatures, potentially approaching room temperature.

Various experimental studies [3,7,8] have demonstrated that superconductivity in cuprates is a bulk three-dimensional (3D) phenomenon rather than a phenomenon confined exclusively to the CuO_2 planes. Consequently, the values of T_c reported for different high- T_c cuprate superconductors correspond to their bulk superconducting transition temperatures.

Since 1993, considerable attention has been devoted to increasing T_c in several families of cuprate superconductors through the application of external pressure [9-11]. The record values of $T_c \simeq 153 - 164$ K reported for Hg-based cuprate superconductors have remained among the highest values achieved in this class of materials. Despite extensive theoretical and experimental efforts over several decades (see Refs. [12-16]), raising T_c to room temperature in high- T_c cuprates has remained a significant challenge. To date, room-temperature superconductivity has not been conclusively established in high- T_c cuprate materials, even under high-pressure conditions.

More recently, considerable interest has focused on the search for room-temperature superconductivity in other classes of materials. In particular, high- T_c hydride superconductors have been synthesized under extremely high pressures [17]. However, superconductivity occurring only under such extreme pressure conditions is unlikely to be suitable for broad practical applications. Consequently, during the past decade, increasing efforts have been directed toward synthesizing promising ceramic cuprate superconductors exhibiting superconducting-transition onset temperatures $T_c^{\text{onset}} \gtrsim 150 - 180$ K at ambient atmospheric pressure, using advanced synthesis techniques [18,19]. Among the most promising materials are Bi/Pb-based ceramic cuprate compounds, such as $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ (with $n = 2 - 30$), which may provide an alternative route toward achieving superconductivity at temperatures approaching or reaching room temperature under ambient-pressure conditions.

For several decades, theoretical studies have suggested that models such as Little's model of high- T_c superconductivity in one-dimensional organic polymers with polarizable side chains [20] and Ginzburg's model involving two-dimensional (2D) alternating conducting and insulating layers [21] could provide possible pathways toward room-temperature superconductivity. These early theoretical approaches were largely based on concepts related to Bardeen-Cooper-Schrieffer (BCS) theory and Fermi-liquid superconductivity. Likewise, many contemporary theoretical studies aimed at discovering new high- T_c superconductors have relied on BCS-like and Migdal-Eliashberg theories to evaluate the possibility of increasing T_c toward room temperature [15-17].

However, high- T_c (cuprates exhibiting a λ -type superconducting transition at T_c [22,23], analogous in some respects to the λ -transition observed in liquid ^4He , may operate within a Bose-liquid superconductivity regime [24,25]. Consequently, conventional BCS-like approaches may be insufficient for describing or predicting the actual transition temperatures of such unconventional superconducting systems.

In previous work [26], theoretical and experimental results were presented indicating signatures consistent with room-temperature superconductivity emerging in

different two-dimensional domains of newly developed Bi/Pb-based ceramic cuprate superconductors containing numerous grain boundaries, interfaces, and multiplate structures. It was demonstrated that, in addition to bulk 3D superconductivity, strongly enhanced 2D superconductivity precursors may occur above the bulk T_c , particularly within the 3D-2D crossover region.

Experimental signatures consistent with room-temperature superconductivity have also been reported at grain boundaries, interfaces, and within multiplate structures of $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ (with $n = 2-30$), ceramic cuprates synthesized using a novel melt-processing technique under concentrated solar energy. These observations were interpreted as evidence for room-temperature superconductivity precursors based on a sharp decrease in electrical resistance and a pronounced partial Meissner effect near 300 K at ambient pressure, torque and Vibrating Reed (VR) measurements.

In the present work, we further investigate these phenomena through a comparative study of samples fabricated using solar-energy-assisted and conventional solid-state reaction techniques. Torque magnetometry and resonant radio-frequency (RF) magnetometry measurements are employed to characterize the superconducting properties of the samples. The results obtained are compared with those reported previously and provide further insight into the superconducting behavior of these Bi/Pb-based ceramic cuprate materials at high temperatures up to room temperature ones.

The development of superconducting materials with the highest possible critical temperature (T_c) depends strongly on the synthesis method employed. The solid-state reaction method is widely used for the preparation of high- T_c cuprate superconductors. However, this approach has several disadvantages. In particular, the synthesis process involves multiple stages, and producing highly textured samples is often difficult.

MATERIALS/METHODS

The development of superconducting materials with the highest possible critical temperature (T_c) depends strongly on the synthesis method employed. The solid-state reaction method is widely used for the preparation of high- T_c cuprate superconductors. However, this approach has several disadvantages. In particular, the synthesis process involves multiple stages, and producing highly textured samples is often difficult.

In this regard, melt-processing technologies are considered promising for the synthesis of high- T_c cuprate superconductors. Compared with conventional synthesis methods, melt processing offers several advantages, including the possibility of obtaining materials with higher critical temperatures and improved textural properties. Various energy sources have been employed to melt mixtures of starting materials, including resistance and induction furnaces, optical furnaces, lasers, and other high-energy sources.

In recent years, a new melt-processing technology has been developed for the synthesis of Bi/Pb-based ceramic cuprate superconductors using concentrated solar energy to melt the starting materials [27]. The advantages of this approach for synthesizing high- T_c ceramic materials have been reported previously [18,19]. The use of concentrated solar radiation provides an effective means of achieving the high temperatures required for melting and allows the preparation of highly textured Bi/Pb-based ceramic cuprate superconductors with the nominal composition $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ ($n = 2-30$). In these

materials, the onset of superconductivity occurs at critical temperatures approaching room temperature.

The samples were synthesized by a melt-processing technique in a large solar furnace located in Parkent. The melting process and synthesis of the ceramic cuprate superconductors $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ are illustrated in Figure 1.

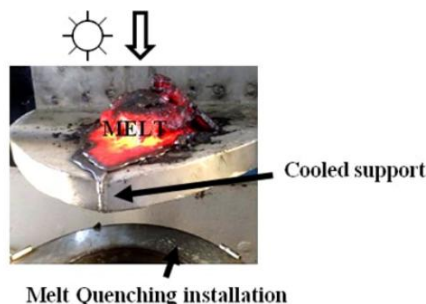


Figure 1: Melting of the starting-material mixture and synthesis of $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ ceramic cuprate superconductors in a large solar furnace.

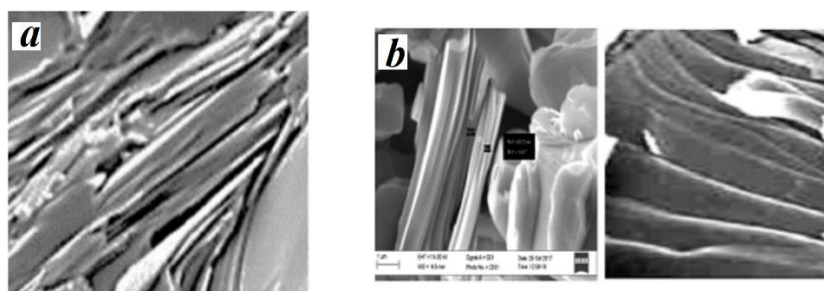


Figure 2: Microstructures of Bi/Pb-based ceramic cuprate superconductors: (a) Bi/Pb (2.2.29.30) and (b) Bi/Pb (2.2.19.20), obtained using electron microscopy, Solver Next microscopy, and scanning electron microscopy (SEM) [26].

The nominal compositions $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ were prepared from appropriate mixtures of the precursor materials Bi_2O_3 , PbO , SrCO_3 , CaO , and CuO . The mixtures were placed in the solar furnace and melted using concentrated solar radiation with a radiant flux of approximately $420\text{--}480\text{ W/cm}^2$, as shown in Figure 1. During the melting process, temperatures of approximately 1480°C were achieved.

The synthesized samples were prepared in the form of bars or plates measuring $5 \times 5 \times 45\text{ mm}$, as well as disks with diameters ranging from 14 to 26 mm and thicknesses of 2.3–5.4 mm. The microstructures of the resulting samples were investigated using Solver Next microscopy, scanning electron microscopy (SEM), and a Zeiss electron microscope. Phase identification and structural analysis were performed using X-ray diffraction (XRD) with a DRON-4 UM-1 diffractometer using $\text{Cu K}\alpha$ radiation and a Ni filter.

The prepared Bi/Pb-based cuprate superconductors exhibited complex microstructures characterized by numerous grain boundaries oriented approximately parallel to one another, as well as twin boundaries, interfaces, and multilayered plate-like blocks, as shown in [26] (Figure 4).

RESULTS

1) Experimental Evidence of Room-Temperature Superconductivity Signatures in Bi/Pb-Based Ceramic Cuprate Superconductors Based on Resistance and Partial Meissner Effect Measurements

According to the X-ray diffraction results and the observed resistive transitions, the synthesized Bi/Pb-based cuprate superconductors are multiphase materials in which different superconducting phases emerge at different critical temperatures. In particular, three-dimensional (3D) superconducting phases with different bulk critical temperatures (T_c) are observed in the temperature range of approximately 100-130 K.

Electron microscopy investigations of the ceramic samples revealed a complex microstructure consisting of small and large grains (nanocrystals), twin domains, and closely packed, parallel multilayer blocks, as illustrated in Figure 2. The ceramic chips obtained from glass-crystalline plates and subsequently annealed at approximately 843-850°C for 3-94 h exhibit closely packed multilamellar blocks. These blocks contain coupled stacks of numerous quasi-two-dimensional parallel layers with nanoscale thickness.

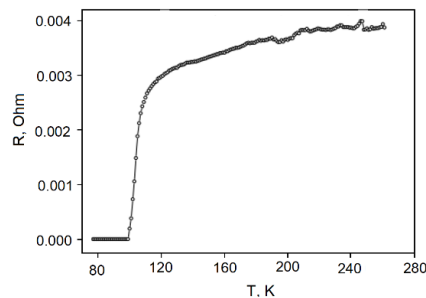


Figure 3: Temperature dependence of the resistance of the Bi/Pb-2245 sample.

The superconducting properties of the Bi/Pb-based ceramic cuprate samples were investigated over a broad temperature range of 77-300 K. The critical temperatures of the superconducting transitions were determined from resistance-temperature measurements [26] using the standard four-probe method with silver paste electrical contacts. In all cases, the contact resistance was below 1 Ω . The superconducting transition temperature was determined from the maximum slope of the resistive transition in the resistance-temperature curves.

Figure 3 presents the resistance-temperature dependence of the synthesized $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ (Bi/Pb-2245) sample. The onset of superconductivity in the 2D domains appears at an onset temperature (T_c^{onset}) of approximately 210 K, which is considerably higher than the bulk critical temperature of about 120 K.

Figure 4 shows the corresponding resistance-temperature dependence for the Bi/Pb-2267 sample. In this material, the onset of superconductivity is observed near room temperature, with $T_c^{\text{onset}} \approx 295$ K, accompanied by a sharp, step-like decrease in resistance. Similarly, the Bi/Pb-221920 sample exhibits a superconducting onset at approximately 310 K, followed by a pronounced drop in resistance around this temperature (Figure 5).

For the Bi/Pb-222930 sample, shown in Figure 6, the resistance initially increases slightly as the temperature decreases from approximately 350 K to 295 K. A sharp decrease

in resistance then occurs near 295 K, producing a distinct step in the superconducting transition. The corresponding onset temperature is approximately 295 K.

Upon further cooling, additional superconducting transitions are observed in the Bi/Pb-2245, Bi/Pb-2267, Bi/Pb-221920, and Bi/Pb-222930 samples at temperatures of approximately 100-130 K. These observations suggest that bulk 3D superconductivity in the Bi/Pb-based ceramic cuprates develops at significantly lower temperatures than the initial onset of 2D superconductivity. The higher-temperature superconducting behavior appears to originate from grain boundaries, 3D/2D interfaces, and the multilayer blocks present within the ceramic structure.

The step-like resistive transitions observed near room temperature are characteristic of the multiphase nature of these superconductors. They may indicate the presence of more than one superconducting phase and the persistence of remnant 2D superconducting regions above the bulk critical temperature. Thus, the experimental results suggest that 3D and 2D superconducting phases can coexist below the bulk T_c . At temperatures below the bulk critical temperature, however, the ceramic samples are predominantly composed of the 3D superconducting phase.

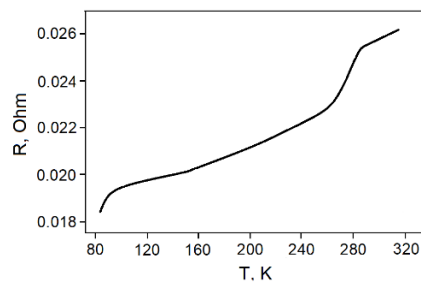


Figure 4: Temperature dependence of the resistance of the Bi/Pb-2267 sample.

Another important criterion proposed for room-temperature superconductivity in the synthesized $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ samples is the observation of a pronounced Meissner effect below the characteristic temperature associated with the step-like resistive transition near room temperature. An incomplete Meissner effect was detected in most of the investigated ceramic superconducting samples at room temperature.

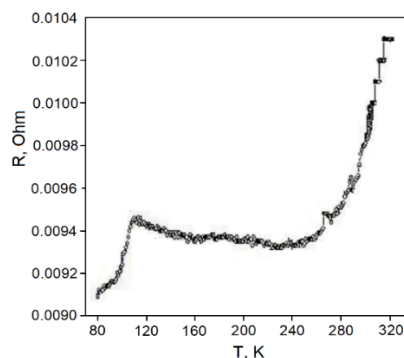


Figure 5: Temperature dependence of the resistance of the Bi/Pb-221920 sample

Figure 7 illustrates the observed Meissner effect, corresponding to the expulsion of magnetic flux from the Bi/Pb-based ceramic cuprate superconductor at room temperature. As the temperature decreases, the fractional Meissner effect gradually increases. However, it remains below 100%, even at temperatures lower than the bulk T_c . This incomplete magnetic shielding may be associated with the presence of insulating regions within underdoped and optimally doped high- T_c cuprate superconductors [28-30].

In insulating domains, Cooper pairs are proposed to become localized in real space rather than remaining delocalized in momentum space, forming localized pairs or bipolarons [31], as previously observed in Bi-2212 [32]. Consequently, variations in the Meissner response of ceramic high- T_c cuprate superconductors can reflect changes in the relative volumes of insulating regions and superconducting 3D and 2D domains.

Based on these observations, it can be estimated that the superconducting volume fraction associated with the 2D domains in the investigated Bi/Pb-based cuprate samples, and consequently the partial Meissner effect detected at room temperature, may range from approximately 5% to 25%.

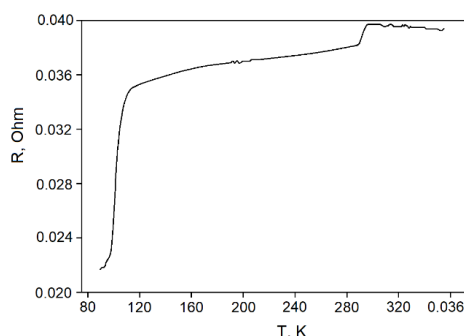


Figure 6: Temperature dependence of the resistance of the Bi/Pb-222930 sample.



Figure 7: Partial Meissner effect detected at room temperature in the $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ ($n = 30$) Bi/Pb-based ceramic cuprate superconductor.

2) Experimental Evidence of Room-Temperature Superconductivity Signatures in Bi/Pb-Based Ceramic Cuprate Superconductors by Torque and Vibrating-Reed (VR) Magnetometry Methods

The nature of superconducting (SC) precursors in cuprate superconductors has been the subject of extensive investigation. Different experimental techniques have produced different conclusions regarding the temperature range over which superconducting fluctuations persist above the bulk critical temperature, T_c . One of the principal challenges

is to distinguish the superconducting contribution from the complex magnetic response of the normal state.

To address this problem, torque magnetometry was employed in [33]. This technique provides a highly sensitive thermodynamic probe of superconducting diamagnetism. In torque magnetometry, the magnetization M is determined from the mechanical torque

$$\tau = M H \sin\alpha,$$

where H is the applied magnetic field and α is the angle between the magnetization and the magnetic field. The torque is measured as a function of temperature T , magnetic-field strength H , and the orientation of the sample relative to the applied field.

An important advantage of this approach is its ability to separate the superconducting response from contributions associated with the normal state. This makes it possible to detect weak diamagnetic signals above the bulk T_c with high sensitivity. The measurements revealed that the superconducting diamagnetism disappears in an unusual and apparently universal manner. This behavior may be associated with the proliferation of superconducting clusters arising from the intrinsic nanoscale inhomogeneity of cuprate materials.

These results are significant because they provide a thermodynamic indication of the emergence of superconducting precursors above the bulk transition temperature. Diamagnetism is one of the fundamental characteristics of superconductivity, and its observation provides a direct probe of the superconducting state that does not depend on modeling the complex normal-state background. As discussed in [33], the unusual development of superconducting precursors may be related to the lamellar, perovskite-derived structure of cuprates and their intrinsic nanoscale electronic inhomogeneity. Such inhomogeneity has also been observed using scanning tunneling microscopy (STM) and nuclear magnetic resonance (NMR) techniques.

Consequently, spatially inhomogeneous superconducting gaps may persist locally in the form of superconducting precursor clusters at temperatures substantially above the bulk T_c . With decreasing temperature, these clusters increase in number and size and eventually form a connected network near T_c . Within this picture, the emergence of bulk superconductivity can be regarded as a percolation process, with the relevant temperature scale determined by the distribution of superconducting gaps rather than solely by the bulk T_c .

The critical temperatures of the superconducting transitions were also investigated using an ultrasensitive magneto-mechanical torsional technique implemented in an automated multipurpose device [34,35]. The sensitivity of this system was comparable to that of a SQUID magnetometer. Measurements were performed using low-frequency axial-torsional oscillations in the range of approximately 0.1-1 Hz in a permanent magnetic field of strength H . The results demonstrated a substantial dependence of the measured response on the experimental background, magnetic-field strength, initial sample orientation, and the direction of temperature variation, i.e., cooling or warming.

The axial-torsion system was particularly sensitive to the reorientation of magnetic moments in an applied magnetic field. Since high-temperature superconductors possess magnetic moments and exhibit complex magnetic behavior, this type of measurement is

useful for investigating structural and magnetic transitions, including those occurring in the normal state at $T > T_c$.

The axial-torsional-oscillation technique was initially developed for investigating energy losses and dissipation in the mixed state of hard superconductors [36]. The exceptionally high sensitivity of the torsional system, reaching approximately 10^{-17} W, made it possible to determine important superconducting parameters, including T_c and the lower critical magnetic field H_{c1} . The method also enabled investigations of the anisotropy of vortex pinning forces and the intrinsic magnetic properties of high-temperature superconducting (HTSC) materials.

Such measurements provide information relevant to the symmetry of the superconducting order parameter and, consequently, to the mechanisms responsible for electron pairing and high-temperature superconductivity. Furthermore, analysis of dissipative processes in the vicinity of T_c provides an opportunity to investigate the melting of the Abrikosov vortex lattice.

Using this technique, the superconducting transition temperature can be determined not only from the temperature dependence of the oscillation frequency, $\omega = 2\pi/t$, in a permanent magnetic field H , but also from the temperature dependence of the logarithmic decrement of attenuation, $\delta(T)$. The simultaneous measurement of the oscillation period $t(T)$ and the damping parameter $\delta(T)$ provides complementary information about the presence and dynamics of magnetic vortices and therefore about the superconducting state of the sample.

Previous investigations of vortex pinning and dissipation employed the original low-frequency vibrating-torsion mechanical magnetometry technique, using the automated multipurpose device [34], together with conventional magnetic and electrical measurements. These studies demonstrated that samples synthesized using SFAQ-T technology were multiphase and contained phases with critical temperatures exceeding 200 K. However, the concentration of these high- T_c superconducting phases was very low, making more sensitive experimental techniques necessary for their reliable identification.

One such technique is VR magnetometry, a comparatively high-frequency method developed independently in [37,38]. Because the resonance frequency and dissipation of the vibration reed can be measured with high precision, the VR technique provides greater sensitivity than conventional AC susceptometry. It allows the elastic coupling between the Abrikosov vortex lattice and the crystal lattice to be investigated even in micron-sized HTSC grains embedded in a normal matrix.

Measurements of the VR resonance frequency and dissipation as functions of the external magnetic field H can be used to determine the temperature dependence of the lower critical field H_{c1} without introducing additional fitting parameters. At the same time, the dissipative response provides information about energy losses associated with the motion of the Abrikosov vortex lattice.

In [39], the VR technique was applied to two-phase Bi-Ca-Sr-Cu-O superconducting ceramics for precise determination of their bulk critical temperatures. Subsequently, the method was used in [34,35] to investigate superconducting precursor phases above the bulk T_c . These measurements demonstrated that VR magnetometry possesses sufficient

sensitivity to superconducting diamagnetism to reveal weak superconducting precursor phases at temperatures above the bulk transition.

The electronic part of the experimental system consists of an acoustic spectrometer operating at a frequency of approximately 1 kHz, together with a system for generating the magnetic field. The spectrometer provides measurements of the natural resonance frequency f_r of the sample with an accuracy of approximately 0.1%.

In the VR acoustic spectrometer, bending oscillations of a rectangular plate-shaped sample are excited electrostatically. The electronic system operates in a self-excitation mode, allowing the sample to oscillate at its natural resonance frequency. An electrode positioned close to the sample forms a capacitance that is incorporated into the oscillating circuit of a high-frequency generator and simultaneously serves to excite and detect the sample oscillations.

Measurement of the resonance frequency f_r makes it possible to determine the elastic modulus E according to the corresponding relation:

$$f_r = k \frac{d}{L^2} \sqrt{\frac{E}{\rho}},$$

where d is the sample thickness, L is the length of the oscillating plate, ρ is its density, and k is a geometrical constant.

The variation of the square of the resonance frequency, (f^2), can be interpreted within the framework of the magneto-mechanical approach developed in [37]. When a superconducting sample is displaced relative to an external magnetic field H , restoring forces act on magnetic vortices that are pinned within the material. Consequently, the resonance frequency of the sample changes by an amount $\Delta f(H)$, which depends on the density of pinned vortices, the moment of inertia, and the volume of the superconducting material.

The dependence of the effective elastic modulus of the substrate-sample system, expressed through f^2 , on the applied magnetic field provides information about the elastic interaction between the Abrikosov vortex lattice and the crystal lattice. This makes VR magnetometry a useful technique for determining vortex-pinning forces. In addition, the $f^2(H)$ dependence can be employed to determine the lower critical field H_{c1} .

The temperature dependence of the critical parameters associated with superconducting precursors in the multiphase sample $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{19}\text{Cu}_{20}\text{O}_y$ was first investigated using the low-frequency torque magnetometry technique [34]. Figure 8 presents the corresponding results. For comparison, Figure 8a shows measurements obtained for the single-phase compound $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$. The single-phase sample does not exhibit the additional features associated with superconducting precursor phases that are observed in the multiphase material.

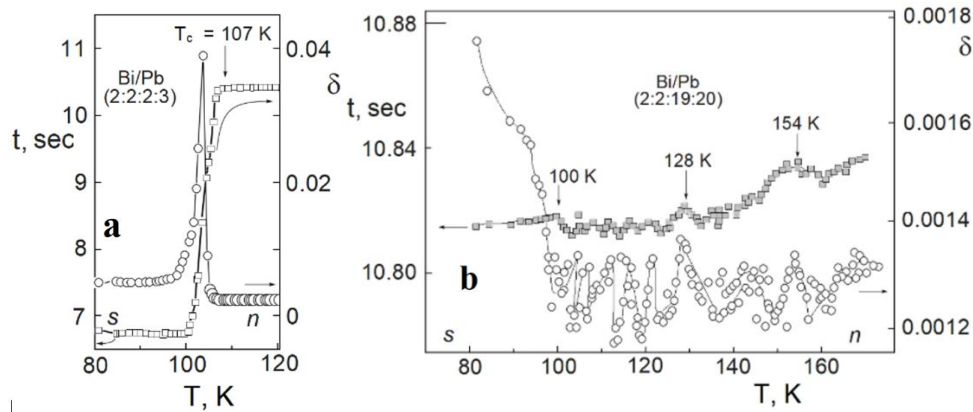


Figure 8: Temperature dependence of the oscillation period t , and logarithmic damping decrement δ in magnetic field $H=150$ mT for a ceramic single-phase sample with nominal composition $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$, and a $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{19}\text{Cu}_{20}\text{O}_y$ sample synthesized from precursors obtained using solar technology [34].

Figure 9 presents the temperature dependences of the squared natural resonance frequencies of the multiphase samples (2-2-8-9) and (2-2-19-20), measured using VR magnetometry [37].

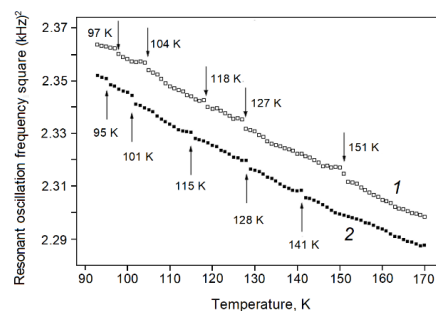


Figure 9: Temperature dependence of the square of the natural resonance frequency for multiphase samples (2-2-8-9) (curve 1) and (2-2-19-20) (curve 2) in a magnetic field of $B=300$ mT [37].

Distinct anomalies are observed in the temperature interval of approximately 90-160 K. In the $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_8\text{Cu}_9\text{O}_y$ sample (curve 1), as well as in the $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{19}\text{Cu}_{20}\text{O}_y$ sample (curve 2), characteristic features occur near 95, 101, 115, 128, and 141 K. These anomalies are attributed to superconducting high-temperature precursor phases present in the multiphase $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{(n-1)}\text{Cu}_n\text{O}_y$ system. Such features are absent in the single-phase sample (2-2-2-3) synthesized by conventional solid-state technology.

The experimental results therefore indicate the presence of several distinct superconducting precursor phases in the (2-2-8-9) and (2-2-19-20) samples. The features observed by VR magnetometry correspond to those detected by the low-frequency torque measurements, while the VR technique provides better separation and resolution of the individual transitions. This agreement represents additional evidence supporting the existence of high-temperature superconducting precursor phases in multiphase $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{(n-1)}\text{Cu}_n\text{O}_y$ ceramics and demonstrates the potential of VR magnetometry as a highly sensitive method for investigating weak superconducting responses in multiphase HTSC materials.

Comparative Resonant RF Magnetometry Study of Samples Fabricated by Solar and Solid-State Reaction Methods

Let us consider the comparative resonant RF magnetometry study of samples fabricated by solar and solid-state reaction methods

The resonant RF magnetometry method used in this study is essentially a low-frequency self-inductance measurement technique [40,41]. A superconducting sample is placed inside a solenoid coil, thereby forming the core of the coil. The coil is incorporated into an LC oscillator operating at a frequency of approximately 900 kHz.

When the external magnetic field is varied, the effective inductance of the coil, L , changes, resulting in a corresponding variation in the oscillator frequency. The fundamental relationship is given by:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

When a sample is introduced into the induction coil, the inductance changes by ΔL . For small changes in inductance, where $\Delta L/L \ll 1$, differentiation of the above relationship gives:

$$\frac{\Delta f}{f} = -\frac{\Delta L}{2L}$$

For a magnetic material, the change in inductance is proportional to the real component, χ' , of the complex magnetic susceptibility [41].

During the measurements, the sample was exposed to a magnetic field generated by a pair of Helmholtz coils. The applied magnetic field was varied over the range $H = 0-200$ Oe. The samples were placed in cylindrical capsules with dimensions of 12×6 mm.

The purpose of this investigation was to study the variation in the resonant frequency, $\Delta f(H)$, of the magnetometer as a function of the applied external magnetic field. A schematic representation of the experimental arrangement is shown in Figure 10.

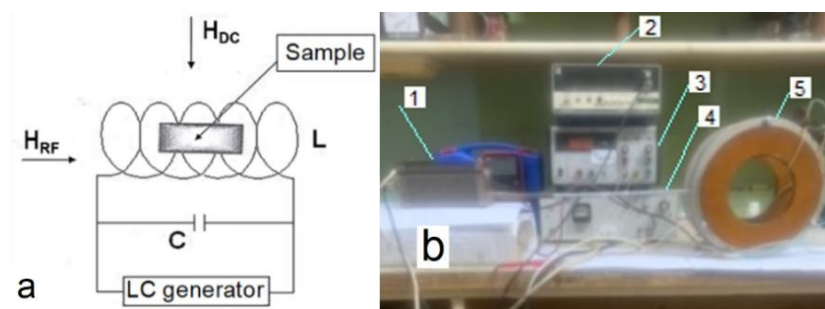


Figure 10: Schematic diagram of the LC generator (a) and experimental setup (b): 1—LC generator, 2—frequency meter, 3—current source, 4—universal power supply, and 5—Helmholtz coils.

The measured $\Delta f(H)$ dependences obtained using the resonant magnetometer are presented in Figure 11.

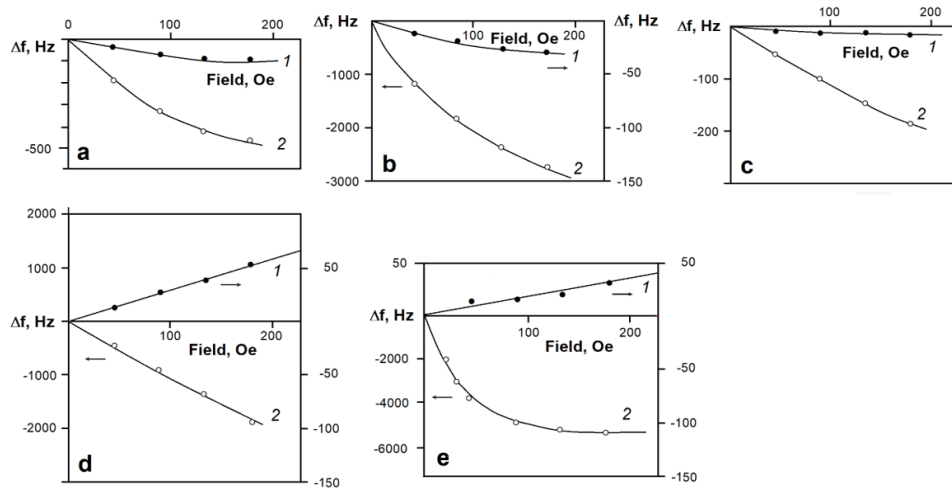


Figure 11: $\Delta f(H)$ dependences for the 221920, 2267, and 222930 samples (a, b, c) and for BSCCO Bi-2223 and YBaCuO samples (d, e) prepared using non-solar technologies. Measurements were performed at room (1) and liquid-nitrogen temperatures (2).

A comparison of the dependences shown in Figures 11 a,b,c for the samples prepared using solar technology with those shown in Figures 11 d,e for samples prepared using conventional, non-solar technologies reveals a pronounced negative diamagnetic frequency shift, $\Delta f(H)$, in samples a, b and c at the room temperature, similar to the large negative frequency shift at the liquid nitrogen temperature. In contrast, this effect is absent in samples d and e.

These observations are consistent with the results reported in Refs. [26,42], which suggest the possible presence of diamagnetic effects in superconducting materials prepared using solar technology, including at room temperature.

CONCLUSION

In conclusion, we have examined the possibility of coexisting three-dimensional (3D) and two-dimensional (2D) superconducting states in multiphase Bi/Pb-based ceramic cuprates with nominal composition $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ ($n = 2-30$) using complementary theoretical and experimental approaches. Within the Bose-liquid framework of unconventional superconductivity [26], the heterogeneous microstructure of these materials can provide distinct superconducting environments in which 3D and quasi-2D states coexist. In this picture, interfaces and low-dimensional regions may support superconducting correlations at temperatures above the bulk 3D transition temperature, $T_c (=T_c^{3D})$.

The model considered here associates superconductivity with strongly bound polaronic Cooper pairs whose condensation depends on the local dimensionality and structural environment. The resulting transition temperature is determined by parameters including the effective boson mass, superfluid-boson density, and interboson interaction. A reduction in dimensionality can therefore modify the superconducting transition and allow superconducting correlations to persist above the temperature at which bulk 3D superconductivity is established. This leads naturally to two characteristic temperature

scales: T_c^{3D} , corresponding to the formation of a macroscopic 3D superconducting state, and a higher characteristic temperature, T_c^{2D} , associated with superconducting correlations in low-dimensional domains or interfacial regions.

From this perspective, the loss of zero resistance above T_c^{3D} should not necessarily be interpreted as the complete disappearance of superconducting correlations. Localized superconducting states may remain at grain boundaries, twin boundaries, 3D/2D interfaces, or within nanoscale and multilamellar structural regions. Such spatially confined superconducting regions could produce measurable electrical and magnetic signatures even when a homogeneous bulk superconducting state is not established.

This interpretation is particularly relevant to the multiphase Bi/Pb-based cuprates produced by advanced melt-processing methods. Their complex microstructure contains numerous interfaces, grain and twin boundaries, and multilamellar regions capable of providing reduced-dimensional environments within the bulk ceramic. The combination of phase heterogeneity and rapid structural evolution during processing may therefore favor the formation or stabilization of superconducting regions with transition temperatures substantially higher than the conventional bulk transition.

Experimentally, samples prepared using solar-energy-assisted synthesis and superfast quenching of the melt (SFAQ-T) exhibited unusually high resistive onset temperatures. For the investigated compositions, electrical measurements gave $T_c^{\text{onset}} \approx 295\text{--}310$ K under ambient pressure. The resistive transition was characterized by a pronounced, step-like reduction in resistance. In addition, a partial Meissner-type response was observed in the vicinity of room temperature. These results indicate the presence of a superconducting-like or superconducting-precursor response at temperatures well above the conventional bulk transition of the material.

Magnetic measurements provide independent evidence supporting this interpretation. Torsional and vibrating-reed magnetometry performed on precursor phases within the multiphase Bi-Pb-Sr-Cu-O system prepared by SFAQ-T processing revealed temperature-dependent behavior consistent with the electrical measurements. The observation of a partial Meissner response is particularly relevant because it provides a magnetic signature independent of the resistive transition. At the same time, the incomplete nature of the magnetic response argues against interpreting the observations as definitive evidence for homogeneous bulk superconductivity throughout the ceramic. A spatially inhomogeneous, filamentary, interfacial, or precursor superconducting state is therefore a more conservative interpretation of the present data.

Additional magnetic measurements were performed using resonant RF magnetometry on $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ samples with $n = 7, 20$, and 30 synthesized using solar energy and SFAQ-T processing. A negative diamagnetic frequency shift was detected near room temperature. Comparison with samples produced by non-solar synthesis routes suggests that the RF response may be associated with high-temperature superconducting precursor phases or localized superconducting regions whose formation is influenced by the particular processing conditions and resulting microstructure. Although these observations require further independent verification, their consistency with the electrical and conventional magnetic measurements provides motivation for additional systematic investigation.

Taken collectively, the results are compatible with a superconducting state that is spatially heterogeneous rather than uniformly distributed throughout the ceramic. The proposed 3D-2D framework offers one possible explanation in which low-dimensional domains and interfacial regions contribute disproportionately to the high-temperature response. In this scenario, the experimentally observed onset temperature need not correspond directly to the establishment of a fully connected bulk superconducting phase. Instead, it may reflect the appearance of localized superconducting correlations that develop above T_c^{3D} within specific structural environments.

The present findings therefore identify multiphase Bi/Pb-based cuprates as a potentially valuable platform for studying high-temperature superconductivity associated with interfaces, reduced dimensionality, and nonequilibrium microstructures. The combination of melt processing, rapid quenching, multiphase organization, and solar-energy-assisted synthesis may provide a route for controlling the formation and distribution of such regions. However, establishing the microscopic origin and superconducting nature of the observed room-temperature response requires substantially more quantitative characterization.

Future investigations should determine the superconducting volume fraction, spatial distribution and connectivity, magnetic shielding fraction, critical current density, field dependence, reproducibility, and spectroscopic characteristics of the proposed high-temperature phases. Independent measurements using complementary experimental techniques will also be essential for distinguishing genuine superconductivity from other possible sources of anomalous electrical and magnetic responses.

Within these limitations, the present electrical, torque and Vibration Reed magnetometry, and RF-magnetometry results provide evidence warranting further investigation of high-temperature superconducting-like states in the Bi/Pb-based cuprate system. If independently reproduced and quantitatively confirmed, the observed onset temperatures approaching 300 K would be of considerable significance and could establish these multiphase materials as a promising platform for exploring ambient-pressure superconductivity near room temperature. The combined experimental observations and 3D-2D theoretical framework consequently provide a basis for continued investigation of the relationship between microstructural dimensionality, interfacial superconductivity, and exceptionally high transition temperatures.

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