Coherency of the superconducting state: the muon spin rotation and ARPES studies of \((\text{BiPb})_2(\text{SrLa})_2\text{CuO6+δ}\)

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The superfluid density \(\rho_s\), being proportional to the density of the supercarriers, is one of the important characteristic of the superconducting condensate. Considering that superconductivity is characterized by the phase coherence of electrons forming the pairs (two-particle process), it was previously believed that techniques which probe the single-particle excitations of the condensate, such as photoemission and single-electron tunneling, could not directly provide the information on \(\rho_s\). It was quite unexpected, therefore, when angle-resolved photoemission (ARPES) studies of the cuprate high-temperature superconductor (HTS) \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8+\delta\) revealed that a sharp peak, formed below the superconducting transition temperature \(T_c\) near the Brillouin zone boundary, contains information not only on the pairing strength (the superconducting energy gap \(\Delta\)) but also on the phase coherence \(\rho_s\). The peak intensity shows a clear resemblance to the behavior exhibited by \(\rho_s\) and scales linearly with \(T_c\) in the underdoped regime \(^1\), \(^2\).

It should be mentioned that previous comparisons between \(\rho_s\) and the coherence peak (CP) were made for CP measured near the Brillouin zone boundary \(^1\), \(^2\). The superfluid density, in its turn, is an “angular integrated” quantity accumulating information over the full Fermi surface. More importantly, the carriers near the antinodes could be affected by the pseudogap, which within “two-gap” scenario is supposed to be unrelated to the pairing \(^3\) \(\sim\) \(^{11}\). This could lead to an additional decrease of the CP intensity in the antinodal region \(^3\). Consequently the CP measurements over the full Brillouin zone are needed in order to compare ARPES data with the superfluid density studied independently in \(e.g.,\) muon-spin rotation (\(\mu\)SR) or microwave experiments.

In this paper we report on the results of \(\mu\)SR studies of the superfluid density and its comparison with the previously reported ARPES data \(^1\) for underdoped \((T_c \approx 23 \text{ K})\), optimally doped \((T_c \approx 35 \text{ K})\) and overdoped \((T_c \approx 29 \text{ K})\) single crystalline (BiPb)\(_2\)(SrLa)\(_2\)CuO\(_{6+\delta}\) samples. It was found that \(\rho_s(T)\) could be well described with a superconducting gap of \(d\)-wave symmetry by introducing the coherence quasiparticle weight function QW measured by means of ARPES. The \(T\) dependence of the superconducting energy gap \(\Delta\) follows the BCS prediction, and \(\rho_s(T = 0)\) scales with the CP intensity integrated over the whole Fermi surface.

Details on the sample preparation of (BiPb)\(_2\)(SrLa)\(_2\)CuO\(_{6+\delta}\) (Bi2201) single crystals can be found elsewhere \(^3\) \(\sim\) \(^^{11}\). The samples are labelled by their superconducting transition temperature \(T_c\) with the prefix UD for underdoped, OP for optimally doped, and OD for overdoped as: UD23K, OP35K, and OD29K. Zero-field (ZF) and transverse-field (TF) \(\mu\)SR experiments were carried out at the \(\pi\)M3 beam line (Paul Scherrer Institute, Switzerland). The samples were cooled from above \(T_c\) to 1.6 K at \(H = 0\) during ZF-\(\mu\)SR experiments and in a series of fields ranging from 5 mT to 0.64 T in TF-\(\mu\)SR experiments. In TF studies the magnetic field was applied parallel to the \(c\) axis and transverse to the muon-spin polarization. The typical counting statistics were \(\sim\) 15 – 18 million muon detections per data point. The TF-\(\mu\)SR data for OP35K are partially published in Refs. \(^4\) \(\sim\) \(^^{15}\).

The representative ZF and TF-\(\mu\)SR time-spectra measured above and below \(T_c\) are presented in the left panels of Figs. \(^1\)a, b, and c. In ZF all three samples show a slow, temperature independent decay thus implying that the \(T\) dependent relaxation observed in TF experiments at \(T < T_c\) should be attributed to the inhomogeneous field distribution in a superconductor in the vortex state. The ZF data for OP35K and OD29K are well described by the Gaussian decay function \(A(t) = A_0 \exp(−\sigma_G^2t^2/2)\) which is caused by the dipolar field arising from the nuclear magnetic moments (\(A_0\) is the initial asymmetry and \(\sigma_G\) is the Gaussian depolarization rate). The exponen-
time-spectra measured above and below magnetic field (right panels) for UD23K (a), OP35K (b), and OD29K (c).

The TF-muSR data were analyzed by using a two-component Gaussian fit of the muSR time-spectra allowing to describe the asymmetric local magnetic field distribution $P(B)$ in a superconductor in the vortex state: $A^{TF}(t) = \sum_{i=1}^{2} A_{i} \exp(-\sigma_{i}^{2}t^{2}/2) \cos(\gamma_{i}B_{i}t + \varphi)$ \cite{14,17,19}. Here $A_{i}$, $\sigma_{i}$, and $B_{i}$ are the initial asymmetry, relaxation rate, and mean field of the $i$-th component, $\gamma_{i} = 2\pi \times 135.5342$ MHz/T is the muon gyromagnetic ratio, and $\varphi$ is the initial phase of the muon-spin ensemble. The weak magnetism detected in ZF experiments for UD23K was taken into account by multiplying the fitting function by $\exp(-\Lambda t)$. The superconducting part of the square root of the second moment $\sigma_{sc} \propto \lambda_{sc}^{-2} \propto \rho_{s}$ ($\lambda_{sc}$ is the in-plane magnetic penetration depth) was further obtained by subtracting the normal state nuclear moment contribution ($\sigma_{nm}$) from the measured second moment of $P(B)$ ($\sigma^{2}$) as $\sigma_{sc} = \sqrt{\sigma^{2} - \sigma_{nm}^{2}}$ \cite{17,14}.

The magnetic field dependence of $\sigma_{sc}$ at $T = 1.6$ K for the samples studied is shown in the corresponding insets of Figs. 1 a, b, and c. The decrease of $\sigma_{sc}$ for OP35K and OD29K is a consequence of both, the nonlinear and the nonlocal response of the superconductor containing nodes in the energy gap to the increasing magnetic field \cite{19}. The solid lines for OD29K and OP35K correspond to fits of the relation $\sigma_{sc}(H)/\sigma_{sc}(H = 0) = 1 - K \cdot \sqrt{H}$ to $\sigma_{sc}(H)$ which takes into account the nonlocal correction to $\rho_{s}$ for a superconductor with a $d$-wave energy gap \cite{20}. The analysis of $\sigma_{sc}(H)$ for UD23K reveals, however, that only at very low fields ($\lesssim 30$ mT) $\sigma_{sc}$ follows the tendency observed for OP doped and OD Bi2201 samples. For higher fields $\sigma_{sc}$ increases with increasing $H$. Such behavior is generally associated with the field induced magnetism and is often observed in various underdoped cuprate HTS (see e.g. Refs. \cite{21,22}).

The observation of the field induced magnetism in UD23K for fields exceeding 30 mT is quite unexpected, especially considering the fact that in their recent study Russo et al. \cite{14} do not detect any kind of field induced effects in Bi2201 with $T_{c} \approx 27$ K up to $\mu_{0}H \approx 5$ T. We may suggest, therefore, that the partial substitution of Bi by Pb, as made in our samples, leads to enhancement of coupling between CuO$_{2}$ layers, thus causing Bi2201 to be more 3-dimensional. This could affect both, the superconducting and the magnetic properties. As for superconductivity, our previous studies point to a substantial reduction of the anisotropy coefficient $\gamma_{\lambda} = \lambda_{c}/\lambda_{ab}$ ($\lambda_{c}$ is the out-of-plane component of the magnetic penetration depth) as well as to the shift of the vortex-lattice melting transition much closer to $T_{c}$ \cite{14}. The magnetic properties could be also affected due to increase of the interlayer magnetic exchange coupling $J'$, which for the layered materials like cuprate HTS is the primary quantity determining the Néel temperature $T_{N} \propto J' \xi_{2D}^{-2}$ ($\xi_{2D}$ is the magnetic correlation length) within the layer.

The temperature dependence of $\lambda_{ab}$ was obtained from the measured $\sigma_{sc}(H = \text{const}, \ T)$’s shown in Fig. 1 by following the procedure described in Ref. \cite{14}. It includes, first, the reconstruction of the effective penetration depth $\lambda_{eff}(H, T)$ from $\sigma_{sc}(H, T)$ by using the relation $\sigma_{sc}(H, T) = 4.83 \cdot 10^{4} |1 - H/H_{c2}(T)|^{1/2} (1 - \sqrt{H/H_{c2}(T)})^{3} \lambda_{eff}^{2}$ \cite{23}. Here $H_{c2}$ is the upper critical field with the zero-temperature values $\mu_{0}H_{c2}(0) \approx 60$ T, $\approx 50$ T and $\approx 45$ T for UD23K, OP35K and OD29K, respectively \cite{23} and with the $T$ dependence following the Werthamer-Helfand-Hohenberg prediction \cite{23}. As a next step, $\lambda_{ab}$ was reconstructed by decomposing $\lambda_{eff}(H, T)$ into the field and the temperature dependent components as $\lambda_{eff}(H/H_{c2}, T) = C(H/H_{c2}) \lambda_{ab}(T)$.

The dependence of $\lambda_{ab}^{-2} \propto \rho_{s}$ on temperature is shown in Fig. 2. For OP35K and OD29K $\lambda_{ab}^{-2}(T)$ was reconstructed from $\sigma_{sc}(H, T)$’s measured at $\mu_{0}H = 0.04$, 0.1,
Here $f$ is the Fermi function, $\phi$ is the angle along the Fermi surface (see the top right panels in Figs. 2a, b, and c), $\Delta(T, \phi)$ denotes the superconducting (pairing) gap depending on $T$ and $\phi$, $\text{QW}(\phi)$ accounts for the relative weight of the quasiparticles condensed into the Cooper pairs, and $S_{\text{QW}} = \int_0^{\pi/4} \text{QW}(\phi)d\phi$. Note that we do not consider here the presence of the second $s$–wave gap $\lambda_{\text{ab}}^2(T = 0)$ and the coherence peak intensity $W_{\text{CP}}$ integrated over the whole Fermi surface on $T_c$. (e) Angular dependence of $W_{\text{CP}}$ measured by ARPES [11].

As a first step we checked if the full spectral gap measured in ARPES experiments (lower right panels in Figs. 2a, b, and c) could be a pairing gap. The solid green lines on the left panels of Figs. 2a, b, and c correspond to the theoretical curves obtained by assuming that the states over the whole Fermi surface are equally available for condensation $\text{QW}(\phi) = 1$, and that the gap in the antinodal region is $T$–independent and it follows the BCS prediction close to the nodes [10]. The poor agreement between the experiment and the theory suggests that the gap near the antinodes could not be related to the pairing. In particular, the step-like jump of $\rho_s$ at $T = T_c$ is due to the fact that the antinodal gap is not closed when the temperature passes through $T_c$.

We suggest, therefore, that for all levels of doping the superconducting (pairing) gap has a $d$–wave symmetry: $\Delta(T, \phi) = \Delta(T) \cos 2\phi$. This is indeed true for OD29K (Fig. 2 and Ref. [11]), as well as for various OD and OP hole-doped cuprate HTS studied by means of ARPES.
(see e.g. Ref. 28 and references therein). The predominantly \textit{d−}wave symmetry of the order parameter in UD HTS was also confirmed in tricrystal experiments 29. This, together with known QW(φ) and λ_{ab}^{-2}(T) allows the use of Eq. (1) to reconstruct Δ(T). The results of such reconstruction for two possible scenarios are shown in Fig. 3 the first with QW(φ) obtained by means of ARPES (see Fig. 2 and Ref. 11), and the second with QW(φ) = 1, indicated by the closed and open symbols respectively. Fits of the BCS model to Δ(T) are represented by solid lines. Both sets of Δ(T) data follow the BCS temperature dependence in agreement with the results of ARPES studies for the spectral gap in the nodal region 11.

**TABLE I: Zero-temperature values of the superconducting gap Δ(0) and the ratio 2Δ(0)/k_{B}T_{c} as obtained from the fit of the BCS model to Δ(T) represented in Figs. 3 a, b, and c.** The "\textit{d−}wave+ QW(φ) = 1" and "\textit{d−}wave+ QW(φ)" refer to the case of QW(φ) = 1 and QW(φ) measured by means of ARPES 11, respectively (see text for details).

|          | Δ(0) (meV) | 2Δ(0)/k_{B}T_{c} | Δ(0) (meV) | 2Δ(0)/k_{B}T_{c} |
|----------|------------|------------------|------------|------------------|
| UD23K    | 4.9(2)     | 4.6(2)           | 8.4(3)     | 8.5(3)           |
| OD35K    | 9.3(2)     | 6.2(1)           | 13.6(3)    | 9.0(2)           |
| OD29K    | 8.6(2)     | 6.9(2)           | 10.3(3)    | 8.2(2)           |

In order to distinguish between the two above mentioned scenarios we note that: (i) Accounting for the quasiparticle weight as measured by ARPES causes a systematic shift of Δ(T) to higher values. This leads to better agreement with the gap obtained from the cos 2θ fit to the ARPES data in the nodal region 11. (ii) The ratio 2Δ/k_{B}T_{c} increases with doping from 4.6 for UD23K to 6.9 for OD29K in a case when QW(φ) = 1 while it stays almost constant (∼ 8.5) for QW(φ) obtained by means of ARPES, see Table I. Note that the independence of 2Δ/k_{B}T_{c} ratio on doping is well confirmed experimentally for various HTS families (see e.g. Refs. 30, 31 and references therein). (iii) The intensity of the coherence peak W_{CP} (Fig. 3e) integrated over the whole Fermi surface scales with the zero-temperature superfluid density (Fig. 3d), thus pointing to the direct relation of W_{CP} to the "local" superfluid density 12, 21, 11. By approaching the antinodal point, W_{CP} decreases thus requiring the corresponding decrease in the local density of the supercarriers. The strongest effect (decrease of W_{CP} down to 0) is observed for UD23K while for OD29K the weight of CP in the nodal region still remains substantial. All these arguments taken together support the scenario according to which the gap (pseudogap) near the antinodes makes a part of the states unavailable for the superconducting condensation and leads, therefore, to a reduced density of the supercarriers in the antinodal region.

To summarize, the temperature dependence of the superfluid density ρ_{s} was studied in underdoped (T_{c} ≃ 23 K), optimally doped (T_{c} ≃ 35 K) and overdoped (T_{c} ≃ 29 K) single-crystalline Bi2201 samples by means of muon-spin rotation. By comparing the measured ρ_{s}(T) with that calculated theoretically based on the results of ARPES 11 we found that the superconducting gap in Bi2201 at all levels of doping has \textit{d−}wave symmetry and that Δ(T) follows reasonably well the BCS prediction. It was also shown that ρ_{s}(T) is inconsistent with the case when the carriers over the whole Fermi surface are equally available for condensation thus suggesting that some parts of the Fermi surface do not develop the superconducting coherence.

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