Reply to Comment on ‘The pairing mechanism of high-temperature superconductivity: experimental constraints’

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Abstract

In our recent paper entitled ‘The pairing mechanism of high-temperature superconductivity: experimental constraints’ (Zhao 2011 Phys. Scr. \textbf{83} 038302), we review some crucial experiments that place strong constraints on the microscopic pairing mechanism of high-temperature superconductivity in cuprates. In particular, we show that phonons rather than spin–fluctuation play a predominant role in the microscopic pairing mechanism. We further show that the intrinsic pairing symmetry in the bulk is not d-wave, but extended s-wave (having eight line nodes) in hole-doped cuprates and nodeless s-wave in electron-doped cuprates. In contrast, the author of the Comment (Plakida 2011 Phys. Scr. \textbf{83} 038303) argues that our conclusions are unconvincing and even misleading. In response to the criticisms in the comment, we further show that our conclusions are well supported by experiments and that his criticisms show a lack of scientific ground.

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(Some figures in this article are in colour only in the electronic version.)
substantial OIE on the in-plane effective supercarrier mass in nearly optimally doped BSCCO [6]. In the underdoped regime, superconductivity should be better described by the Bose–Einstein condensation of local pairs in the strong coupling limit [7]. In this case, $T_c$ is essentially proportional to $n_s/m_{ab}^*$ (where $n_s$ is the supercarrier density and $m_{ab}^*$ is the in-plane effective supercarrier mass), in agreement with the well-known Uemura plot [8]. This implies that the OIE on $T_c$ is essentially proportional to the OIE on $m_{ab}^*$. This scenario can naturally explain why the magnitudes of the exponents for the OIE on both $T_c$ and $m_{ab}^*$ increase with decreasing doping and are even larger than 0.5 in deeply underdoped samples (e.g. La$_{1.85}$Sr$_{0.15}$CuO$_4$) [1, 9]. Therefore, the claim that the polaronic effects cannot explain the doping dependence of the OIE on $T_c$ shows a lack of scientific ground.

Then the author of the Comment [2] attempts to explain the doping dependence of the OIE on $T_c$ in terms of his own theory based on the $t$–$J$ model. According to his model [2], $\Delta T_c/T_c = (1/\lambda)\Delta J/J$, where $\lambda = 0.2–0.3$. Since the OIE on $J$ was found to be about 0.9% for undoped YBa$_2$Cu$_3$O$_6$ [10], the predicted $\Delta T_c/T_c$ for the optimally doped YBa$_2$Cu$_3$O$_{6.84}$ (YBCO) should be about (2.7–4.5)% in disagreement with the measured value of $0.27\%$ [11]. In the deeply underdoped regime, $T_c \propto 1/m_{ab}^*$ and $1/m_{ab}^* \propto J$ within the $t$–$J$ model, so $\Delta T_c/T_c = \Delta J/J = (0.6–0.9)\%$, in disagreement with the measured values of $(-5–12)\%$ [9]. Therefore, the $t$–$J$ model cannot explain the doping dependence of the OIE on $T_c$. Further, the author of the Comment [2] argues that since the site-selective OIE shows that the OIE on $T_c$ mainly contributes from the planar oxygen, the apical oxygen is not important for the pairing. This argument runs parallel with the statement that since the optimally doped YBa$_2$Cu$_3$O$_{6.84}$ has a negligible OIE on $T_c$, phonons are not important for the pairing mechanism. In fact, the site-selective OIE experiment [12] shows that the apical oxygen contributes about 40% of the OIE on $m_{ab}^*$ in YBa$_2$Cu$_3$O$_{6.84}$. This suggests that the apical oxygen is important for the pairing, in agreement with our argument based on the bulk-sensitive x-ray absorption experiment [13] on (Y$_{1-x}$Ca$_x$)$_2$Ba$_2$CuO$_{6.75}$.

The author of the Comment also criticizes the conclusion about strong coupling to multiple phonon modes revealed by both tunneling [4, 5, 14–17] and angle-resolved photoemission spectra (ARPES) [17, 18]. There are several important facts about the strong-coupling features revealed by both tunneling and ARPES data. Firstly, the energies of strong-coupling features match very well with those of the phonon modes revealed by the neutron [15] and Raman [15] data. Secondly, the energies of strong-coupling features revealed by tunneling spectra match very well with those of strong-coupling features revealed by ARPES [17]. Thirdly, the energies of strong-coupling features in different cuprate systems such as LSCO, YBCO and BSCCO are very similar [14, 17, 18] and nearly independent of doping [19]. Such excellent consistencies unambiguously demonstrate that these strong-coupling features are intrinsic and arise from strong electron–phonon interactions. Furthermore, a detailed review of tunneling, ARPES and optical experiments was recently given by Maksimov et al [19]. These authors provide consistent evidence for strong coupling to multiple phonon modes from the tunneling, ARPES and optical results.

Concerning the spin–fluctuation pairing, we have shown that the magnetic resonance mode revealed by neutron experiments plays a minor role in high-temperature superconductivity [1, 16]. One might argue that since the magnetic resonance mode is only a small fraction of the spin-excitation spectrum [20], its contribution to the electron pairing should be insignificant, while the coupling to the whole spin-excitation spectrum may still play an important role in the d-wave pairing. A recent theoretical calculation [21] has shown that strong coupling to the whole spin-excitation spectrum of underdoped YBa$_2$Cu$_3$O$_{6.6}$ (measured by neutron scattering) can lead to d-wave high-temperature superconductivity with $T_c = 174$ K and the coupling constant $\lambda_d = 1.39$. It is important to note that the authors of [21] have used a large renormalized coupling strength $\tilde{U}$ (1.59 eV), which is too large compared with that estimated from several other independent experiments (see the recent review article [19]). These experiments consistently show that $\vert\tilde{U}\vert > 0.17$ eV. This implies that $\lambda_d < 0.0115$ (since $\lambda_d \propto \tilde{U}^2$). Such a small coupling constant cannot lead to high-temperature superconductivity. In addition, neutron scattering data [22] of slightly underdoped YBa$_2$Cu$_3$O$_{6.92}$ and slightly overdoped YBa$_2$Cu$_3$O$_{6.97}$ are difficult to understand in terms of the spin-fluctuation pairing mechanism. The two compounds have almost the same $T_c$ (91–93 K), but the magnetic spectral weight for YBa$_2$Cu$_3$O$_{6.97}$ is at least three times smaller than that for YBa$_2$Cu$_3$O$_{6.92}$. As pointed out by Maksimov et al [19], the small dependence of $T_c$ on the magnetic spectral weight is incompatible with the magnetic pairing mechanism. On the theoretical side, recent variational Monte Carlo simulations [23], which are based on an advanced sign-problem-free Gaussian-basis Monte Carlo algorithm, have shown that the simplest Hubbard model, advocated by Plakida and some other authors, does not account for high-temperature superconductivity.

Another important issue is the intrinsic pairing symmetry in the bulk of superconducting cuprates. Because nearly all the surface and phase-sensitive experiments for both electron- and hole-doped cuprates provide clear evidence for d-wave order–parameter (OP) symmetry [24], the d-wave pairing symmetry has become an indisputable fact for most researchers in the field. However, it is important to note that these surface- and phase-sensitive experiments based on planar Josephson tunneling are probing the OP symmetry at surfaces and interfaces which were found to be underdoped [25, 26]. Since the majority of charge carriers are oxygen–hole bipolarons in the underdoped regime [1] and the OP symmetry of the Bose–Einstein condensate of the oxygen–hole bipolarons is d-wave [27], the phase-sensitive experiments just probe the d-wave OP symmetry of the dominant component. Since the OP symmetry of the Bose–Einstein condensate has nothing to do with the pairing symmetry, the phase-sensitive experiments do not probe the pairing symmetry associated with the pairing interaction. To probe the intrinsic pairing symmetry, bulk-sensitive data should be obtained from significantly overdoped samples where the dominant charge carriers are Fermi liquid like and the superconducting transition is mean field like [1]. Based on the quantitative analyses of many bulk-sensitive experiments (in addition to some bulk- and phase-sensitive...
experiments such as nonmagnetic pair-breaking effects), we have concluded that the intrinsic pairing symmetry in the bulk of cuprates is not d-wave, but extended s-wave (having eight line nodes) in hole-doped cuprates [28] and nodeless s-wave in electron-doped cuprates [29, 30].

The author of the Comment does not believe the intrinsic pairing symmetry inferred from the bulk- and phase-sensitive nonmagnetic pair-breaking effects. He argues against the extended s-wave gap symmetry using the surface-sensitive ARPES and Fourier transform scanning tunneling spectroscopy (FT-STM) experiments [2]. Even surface-sensitive ARPES data of nearly optimally doped BSCCO can be better explained in terms of an extended s-wave gap [17, 28, 31]. The gap along the diagonal direction $\Delta_D$ is small ($\leq 7$ meV) for nearly optimally doped BSCCO [17, 31] but becomes larger in heavily overdoped BSCCO [28, 32]. Furthermore, both surface-sensitive ARPES and FT-STM data of a nearly optimally doped BSCCO can also be well explained in terms of an extended s-wave gap with $\Delta_D \simeq 4$ meV [31]. The significant uncertainty in extracting the gap size from the ARPES data in a slightly overdoped and two underdoped BSCCO crystals [33] does not allow one to make a distinction between a d-wave gap and an extended s-wave gap with $\Delta_D \leq 4$ meV. In fact, no ARPES data along the diagonal direction were given in the study [33], which makes it harder to draw a definitive conclusion about the gap symmetry from the ARPES data.

In order to further prove our extended s-wave pairing symmetry in hole-doped cuprates, we determine the $\Delta_D$ value from some high-resolution ARPES data. The fitting method used in [34] for extracting the gap size from ARPES data should be quite reliable since the gap sizes extracted from this method match precisely with those independently determined from the FT-STM data [31]. Figure 1 shows photoemission spectrum along the diagonal direction for a nearly optimally doped Bi$_2$Sr$_2$Ca$_2$Cu$_2$O$_{8+y}$ (Bi-2223). The spectrum was taken with an energy resolution of 10 meV [36]. The solid line is the curve calculated with the fitting method of [34] and the following parameters: $\Delta_D = 7.0$ meV and $\Gamma = 9.0$ meV.

In figure 2, we show photoemission spectra along the diagonal direction for a nearly optimally doped BSCCO (figure 2(a)) and a heavily overdoped BSCCO (figure 2(b)). The spectra for the nearly optimally doped and heavily overdoped BSCCO crystals were taken with energy resolutions of about 6 and 10 meV, respectively [32, 37]. The solid lines are the curves calculated with the following parameters: $\Delta_D = 6.0$ meV and $\Gamma = 6.0$ meV for the nearly optimally doped BSCCO; $\Delta_D = 14$ meV and $\Gamma = 18$ meV for the heavily overdoped BSCCO. It is striking that $\Delta_D$ increases with increasing doping, in agreement with the earlier ARPES result [35] and break-junction tunneling experiments [28].

In summary, our conclusions on the phonon-mediated pairing mechanism and s-wave pairing symmetry in cuprates...
are well supported by experiments. The criticisms raised in the comment [2] show a lack of scientific ground although the author of the Comment agrees that there exist polaronic charge carriers and that electron–phonon coupling is strong in cuprates.

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