The hunt for the pairing glue in the cuprates

Quantitative determination of the pairing interaction for high temperature superconductivity in cuprates
Science Advances, **2**, E1501329, 2016. arXiv: 1601.02493

Authors: Jin Mo Bok, Jong Ju Bae, Han-Yong Choi, Chandra M. Varma, Wentao Zhang, Junfeng He, Yuxiao Zhang, Li Yu, and X.J. Zhou.

Recommended with a commentary by Andrey Chubukov, University of Minnesota

The understanding of the microscopic mechanism of pairing in the high-Tc cuprates remains a hotly debated issue with no consensus despite the fact that the problem is now 30 years old. In part, the absence of consensus is because some in condensed-matter community view superconducting cuprates as doped Mott insulators and argue that localization of the electronic states by strong Hubbard-type interaction is a necessary input for any analysis of superconductivity, while the others argue that the pairing mechanism can be fully understood by looking into the doping range in which the systems are metals with a Fermi surface, while electron localization, and related magnetic order, reduce T_c and eventually eliminate superconductivity near half-filling.

There is no consensus, however, even on the part of community which views superconductivity as developing in a metal. Most researchers (but not all) believe that d-wave superconductivity in the cuprates originates from electron-electron (Coulomb) interaction rather than from an exchange by phonons, as in ordinary superconductors. Coulomb interaction may have attractive partial components in non-s-wave channels, as Kohn and Luttinger demonstrated back in 1965 [1], so the very existence of d-wave superconductivity mediated by electron-electron interaction is not a surprise. However, to get T_c of order 100K, one needs substantially strong effective interaction in the d-wave channel. This can be reached if a metal is brought to the vicinity of a critical point beyond which fermions develop some kind of order, either homogeneous, or with a finite momentum. Near a critical point, collective fermionic excitations in a near-critical channel become soft and effective interaction mediated by such soft fermions get enhanced and gives rise to larger T_c. This idea is consistent with the growing experimental evidence for the existence of a quantum-critical point near the doping, where T_c is the highest.

What kind of collective excitations becomes soft and mediates d-wave pairing is he subject of debates. The d-wave gap structure naturally emerges if the pairing mediated by spin fluctuations [2,3]; however the magnetic correlation length is not large at optimal doping, at least in zero magnetic field. Other mechanisms, like pairing by soft charge fluctuations [4], or fluctuations associated with loop current order [5], or a combination of phonon-mediated and spin-mediated pairing [6] or have been also proposed.

In the recent paper, Bok et al have made a noble attempt to extract the effective interaction from the very detailed analysis of the laser ARPES data for two Bi2212 samples, one slightly underdoped, with $T_c = 89K$, and another slightly overdoped, with $T_c = 82K$. Such attempts have been made before [7], however earlier studies didn't attempt to extract the effective fermion-fermion interaction directly from the data, but rather used a particular model for the interaction (e.g., spin-fluctuation scenario), extracted parameters from the fit to the data in the normal state, and then analyzed whether superconducting features (e.g. peak-dip-hump structure of the spectral function) are reproduced. Bok et al have extracted the underlying pairing interaction directly from the normal and anomalous self-energies Σ_n and Σ_a.

To carry out this procedure, they used closed-form expressions for Σ_n and Σ_a in terms of effective dynamical four-fermion interaction with zero momentum transfer $\Gamma(k, \omega; k', \omega')$: $\Sigma(k, \omega) = T \sum_{\omega}' \int dk' \Gamma(k, \omega; k', \omega') G(k', \omega')$, where $G(k', \omega')$ is a Nambu Green's function, and inverted these equations to obtain the full dynamical $\Gamma(q, \Omega)$.

The very procedure that Bok et al used is valid if there is a single soft collective excitation. In this situation, $\Gamma(k, \omega; k', \omega') = (g(k, \omega; k', \omega'))^2 \chi(k - k', \omega - \omega')$, where g is fermion-boson coupling, and χ is a propagator of a boson (see e.g., Ref. [8]). Bok et al assumed that g can be approximated by its static part and argued, based on their data, that the self-energies Σ_n and Σ_a do depend on the location of $\mathbf{k}$ on the Fermi surface, but only weakly depend on $\mathbf{k}$ perpendicular to the Fermi surface. From theory perspective [3,9,10], these two assumptions are simultaneously justified within the Eliashberg approximation [11], and the problem they solved is equivalent to extracting the interaction from the Eliashberg equations for Σ_n and Σ_a.

Within Eliashberg theory, Σ_n and Σ_a are expressed in terms of the quasiparticle residue $Z(\theta, \omega)$ and the gap function $\Delta(\theta, \omega)$, respectively, where θ measures the location of $\mathbf{k}$ on the Fermi surface. Both Δ and Z are expressed in terms of $\chi(q, \Omega)$ via integral equations, which involve integrals over frequency and over θ. To extract $\chi(\cos(\theta - \theta'), \omega - \omega')$ one then needs, as inputs, $\Delta(\theta, \omega)$ and $Z(\theta, \omega)$ in a wide range of θ and ω. Bok et al collected data for $|\omega|$ up to $0.2eV$ along six cuts in momentum space at θ between 20^o and 45^o (45^o is the diagonal direction). This gave then enough information to extract χ with a reasonable accuracy.

There is another complication, associated with the fact that $\Delta(\theta, \omega)$ has a $d-$wave structure $\Delta \propto \cos(2\theta)$ and is expressed in terms of the $d-$wave component of the interaction χ_d, while $Z(\theta, \omega)$ has the full lattice symmetry and is expressed in terms of the s-wave component of the interaction χ_s. In the isotropic approximation then, $Z(\theta, \omega)$ should not depend on θ. Bok et al argued that they can extract both χ_s and χ_d from the ARPES data. Their key results are that (i) Z weakly depends on the location of a fermion on the Fermi surface, i.e., an isotropic approximation is valid, and (ii) $\chi_s \approx \chi_d$, i.e., the effective interaction mediated by a soft boson has nearly equivalent $s-$wave and $d-$wave components.

Taken at face value, these two results place serious constraints on microscopic theories of collective boson-mediated interactions. For interaction mediated by soft antiferromagnetic spin fluctuations, χ_s and χ_d are close in magnitude because the same interaction mediates superconductivity and gives rise to normal self-energy, however the isotropic approximation breaks down and C_4-symmetric $Z(\theta)$ has a larger value in the antinode region (small θ) than along the diagonal. The same holds for an interaction mediated by soft uniaxial charge fluctuations. Bok et al argued that the data are consistent with the idea, put forward by C. Varma in a series of papers [5], that strong self-energy in the normal state (leading to marginal Fermi liquid behavior) and d-wave superconductivity originate from the interaction with near-critical fluctuations of loop-current order. The argument is that loop-current order has zero momentum, which is the "best case scenario" for the validity of the isotropic approximation, and the interaction mediated by loop-current fluctuations has momentum dependence in the form $1 - cos(2\theta - 2\theta')$, in which case the magnitudes of χ_s and χ_d are equivalent.

My take is that the experimental data by Bok et al do, indeed, place constraints on the interaction and are consistent with loop-current scenario. It is entirely possible, however, that the devil is in the details, because, e.g., not too-critical spin fluctuations were earlier argued [2] to also reproduce ARPES data.

One can also try to place an additional constraint by adding to the Eliashberg equations for Δ and Z the additional equation describing the feedback from superconductivity on the form of the propagator of the collective boson $\chi(q, \Omega)$ (such a feedback is not small for electron-mediated pairing [12] and, e.g., gives rise to the neutron resonance [13,14]). Bok et al did obtain the change of $\chi(q, \omega)$ between the normal and the superconducting state, but did not yet analyse self-consistently the feedback from this change on fermions.

The paper by Bok et al ends with the phrase "We would urge testing of other idea and calculations with the experimental results". This is clearly called for, and the results by Bok et al provide a unique opportunity for theorists to take their favorable model of electron-mediated pairing, compute Σ_n and Σ_a using the full set of Eliashberg-type equations, including the feedback from superconductivity on fermions and verify whether they can reproduce the experimental data on complex $\Delta(\theta, \omega)$ and $Z(\theta, \omega)$.

1. W. Kohn, J.M. Luttinger, Phys. Rev. Lett. **15**, 524 (1965); J.M. Luttinger, Phys. Rev.**150**, 202 (1966).

2. see e.g., D. J. Scalapino, Rev. Mod. Phys. **84**, 1383 (2012) and references therein.

3. A. Abanov, A. V. Chubukov and J. Schmalian, Adv. Phys. **52**, 119 (2003).

4. C. Castellani, C. Di Castro, and M. Grilli, Phys. Rev. Lett. **75**, 4650 (1995); S. Lederer, Y. Schattner, E. Berg, and S.A. Kivelson, Phys. Rev. Lett. **114**, 097001 (2015); Y. Wang and A. V. Chubukov, Phys. Rev. B 92, 125108 (2015).

5. C. M. Varma, Phys. Rev. B **55**, 14554 (1997).

6. E. van Heumen *et al*, Phys. Rev. B 79, 184512 (2009); S. Johnston *et al* Phys. Rev. B **82**, 064513 (2010).

7. A.A. Kordyuk *et al*, Phys. Rev. Lett. **89**, 077003 (2002)J. Fink *et al*, Phys. Rev. B 74, 165102 (2006); T. Dahm *et al* Nature Physics 5, 217 - 221 (2009).

8. A.A. Abrikosov, L.P. Gorkov, and I.E. Dzyaloshinski, "Methods of Quantum Field Theory in Statistical Physics", Dover Publications, 1975.

9. A.B. Migdal, Sov. Phys. JETP, **7**, 996 (1958).

10. R. Haslinger and A. V. Chubukov Phys. Rev. B 68, 214508 (2003).

11. G.M. Eliashberg. Sov. Phys. JETP **11**, 696 (1960).

12. Ar. Abanov and Andrey V. Chubukov Phys. Rev. Lett. 83, 1652 (1999).

13. H.F. Fong et al, Phys. Rev. B **54**, 6708 (1996); P. Dai et al, Science **284**, 1344 (1999).

14. see e.g. M. Eschrig, Adv. Phys. **55**, 47 (2006) and references therein.