Pairing mechanism for high temperature superconductivity in the cuprates: what can we learn from the two-dimensional $t - J$ model?

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More than twenty years have passed since high temperature superconductivity in the copper oxides (cuprates) was discovered by J.G. Bednorz and K.A. Müller in 1986 [1]. Although intense theoretical and experimental efforts have been devoted to the investigation of this fascinating class of materials, the pairing mechanism responsible for unprecedented high transition temperatures T_c remains elusive. Theoretically, the difficulty lies in the fact that this class of materials, as doped Mott-Hubbard insulators [2], involve strong electronic correlations, which renders conventional theoretical approaches unreliable. Recent progress in numerical simulations of strongly correlated electron systems in the context of tensor network representations [3, 4] makes it possible to get access to information encoded in the ground-state wave functions of the two-dimensional $t - J$ model-a minimal model, as widely believed, to understand electronic properties of doped Mott-Hubbard insulators [5–8]. In this regard, an intriguing question is whether or not the two-dimensional $t - J$ model holds the key to understanding high temperature superconductivity in the cuprates. As it turns out, such a key lies in a superconducting state with mixed spin-singlet $d + s-$wave and spin-triplet $p_x(p_y)$-wave symmetries in the presence of an anti-ferromagnetic background [9]. Here, the $d + s$-wave component in the spin-singlet channel breaks $U(1)$ symmetry in the charge sector, whereas both the anti-ferromagnetic order and the spin-triplet $p_x(p_y)$-wave component breaks $SU(2)$ symmetry in the spin sector. Therefore, four gapless Goldstone modes occur. However, even if we resort to the Kosterlitz-Thouless transition [10], *only* the $d + s$-wave superconducting component survives thermal fluctuations. This turns three gapless Goldstone modes, arising from $SU(2)$ symmetry breaking, into two degenerate soft modes, with twice the spin-triplet $p_x(p_y)$-wave superconducting energy gap as their characteristic energy scale: one is a spin-triplet mode observed as a spin resonance mode in inelastic neutron scattering, the other is a spin-singlet mode observed as a A_{1g} peak in electronic Raman scattering. The scenario allows us to predict that pairing is of $d + s$-wave symmetry, with the two degenerate soft modes as the long-sought key ingredients in determining the transition temperature T_c, thus offering a possible way to resolve the controversy regarding the elusive mechanism for high temperature superconductivity in the cuprates.

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Imagine if we would have been able to solve a model system describing doped Mott-Hubbard insulators on a two-dimensional square lattice, whose ground-state wave function is a superconducting state with mixed spin-singlet $d + s-$wave and spin-triplet $p_x(p_y)-$wave symmetries in the presence of an anti-ferromagnetic background, with the order parameters for the s-wave, d-wave, and $p_x(p_y)$-wave superconducting components, together with the anti-ferromagnetic order parameter, shown in Fig. 1, in a proper doping range. Note that Δ_d and Δ_s are, respectively, the spin-singlet d-wave and s-wave superconducting energy gaps, whereas Δ_p is the spin-triplet $p_x(p_y)$-wave superconducting energy gap and N is the anti-ferromagnetic Néel order parameter. A few peculiar features of this state are: (i) Both the 90 degree (four-fold) rotation symmetry and the translation symmetry under one-site shifts are spontaneously broken on the square lattice. (ii) Spin-rotation symmetry $SU(2)$ is spontaneously broken, due to the simultaneous occurrence of both the $p_x(p_y)-$wave superconducting component and the anti-ferromagnetic order. (iii) $U(1)$ symmetry in the charge sector is spontaneously broken, due to pairing in both spin-singlet and spin-triplet channels. Here, we emphasize that the symmetry mixing of the spin-singlet and spin-triplet channels arises from the spin-rotation symmetry breaking, *simply because spin is not a good quantum number*. (iv) All superconducting components are homogeneous, in the sense that their superconducting order parameters are independent of sites on the lattice.

Now let us switch on thermal fluctuations. Suppose we restrict ourselves to a strict two dimensional system. Then, even if the Kosterlitz-Thouless transition [10] is invoked, *only* spin-singlet $d + s$-wave superconducting component survives thermal fluctuations. However, the non-abelian $SU(2)$ symmetry is not allowed to be broken at any finite temperature [11, 12]. This immediately implies that the Goldstone modes arising from the spontaneous symmetry breaking of $SU(2)$ in the spin sector have to be turned into degenerate soft modes, with twice the spin-triplet $p_x(p_y)$-wave superconducting energy gap as their characteristic energy scale: one is a spin-triplet mode associated with the anti-ferromagnetic order, with the momentum transfer (π, π), and the other is a spin-singlet mode associated with the spin-triplet $p_x(p_y)$-wave superconducting component, with the momentum transfer $(0, 0)$. On the other hand, there is nothing to prevent from the breaking of the discrete four-fold rotation symmetry on the square lattice. Actually, this broken symmetry not only manifests itself in the admixture of a small s-wave component to the dominant d-wave superconducting state (see Fig. 1, left panel), but also protects the spin-singlet soft mode that is unidirectional as it arises from the $p_x(p_y)$-wave superconducting component.

Our argument leads to a scenario that, at any finite temperature, the pairing is of $d + s$-wave symmetry, with two degenerate soft modes acting as the key ingredients in deter-