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SPECIFIC CRITERIA FOR DETERMINING THE FERMIONIC AND BOSONIC NATURES OF COOPER PAIRS IN DOPED CUPRATE SUPERCONDUCTORS

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There are key differences between fermionic (weakly-bound) and bosonic (tightly-bound) Cooper pairs and between the superconducting mechanisms of such Cooper pairs in conventional and unconventional superconductors [1]. Because the underlying mechanism of superconductivity in different materials depends on the fermionic or bosonic nature of superfluid charge carriers, which are believed to be Cooper pairs of fermionic quasiparticles. The fermionic or bosonic nature of Cooper pairs in superconducting materials in turn depends on the strength of the attractive interaction between fermionic quasiparticles in them. As is well known, in conventional metals with large Fermi energies $\varepsilon_F>1$ eV [2] and weak electron-phonon coupling [3], the weakly-bound Cooper pairs have fermionic nature. However, in other materials, depending on the strength of the attractive interaction between two fermionic quasiparticles the physical nature of Cooper pairs is distinguishably altered. Actually, for many superconductors, it is not obvious in which cases the Cooper pairs have the fermionic or bosonic nature and which specific criteria should be satisfied for determining the fermionic and bosonic natures of Cooper pairs. Therefore, it is a challenging problem to find the specific criteria for determining fermionic and bosonic natures of Cooper pairs in such systems.
In this work, we examine the possibility of the formation of fermionic and bosonic Cooper pairs in doped copper oxides (cuprates). We show that the Cooper pairs in doped cuprates, depending on the doping level or the Fermi energy ε_F and the characteristic energy ε_A of the attractive interaction between two pairing fermions (e.g., hole carriers), might be either fermionic Cooper pairs (most likely in overdoped cuprates) or bosonic Cooper pairs (e.g., in underdoped and optimally doped cuprates). We argue that when the size of a Cooper pair a_c in any superconductor is larger than the average distance R_c between Cooper pairs, this large Cooper pair consisting of two Fermi particles has the fermionic nature and such large Cooper pairs strongly overlapping with each other exist most likely in superconductors with $\varepsilon_F \gg \varepsilon_A$. In this case the Fermi components of large Cooper pairs go over from one Cooper pair to another one. As a result, strongly overlapping Cooper pairs behave like fermions. However, at $R_c>a_c$ the Fermi components of Cooper pairs cannot move from one Cooper pair to another one and the non-overlapping nearly small Cooper pairs behave like bosons. It is natural to believe that the bosonic nature of Cooper pairs becomes apparent when $R_c>a_c$.
We obtain the universal and specific criteria for determining the fermionic and bosonic nature of Cooper pairs and the existence of the Bardeen-Cooper-Schrieffer (BCS) –type and non-BCS (i.e. Bose) - type superconductors in condensed matter systems in terms of two characteristic ratios $\varepsilon_A/\varepsilon_F$ and Δ_F/ε_F (where Δ_F is the BCS-like energy gap in the excitation spectra of superconductors). We find that the Cooper pairs in superconductors with $\varepsilon_F>2\varepsilon_A$ have the fermionic nature under the condition $\Delta_F< [(\varepsilon_A \varepsilon_F^2/36\pi)]^{(1/3)}$, while the Cooper pairs in superconductors with $\varepsilon_F<2\varepsilon_A$ have the bosonic nature under the condition $\Delta_F> [(\varepsilon_A \varepsilon_F^2/36\pi)]^{(1/3)}$. We demonstrate that the doped cuprates above a certain overdoping level are in the fermionic limit of Cooper pairs at relatively large Fermi energies $\varepsilon_F>0.3$ eV, but the underdoped, optimally doped and moderately overdoped cuprates are in the bosonic limit of Cooper pairs at small Fermi energies ε_F☒0.2 eV. We conclude that the conventional BCS-type Fermi-liquid superconductivity would occur in overdoped cuprates with ε_F☒0.3 eV, while the unconventional (Bose-liquid) superconductivity would emerge in underdoped, optimally doped and moderately overdoped cuprates with small Fermi energies ε_F☒0.1 eV,ε_F☒0.15 eV and $\varepsilon_F<0.3$ eV, respectively.

References

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