The estimation of coherence length for electron-doped superconductor Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$

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Abstract

Results of low-temperature upper critical field measurements for Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$ single crystals with various $x$ and nonstoichiometric disorder ($\delta$) are presented. The coherence length of pair correlation $\xi$ and the product $k_F\xi$, where $k_F$ is the Fermi wave vector, are estimated. It is shown that for investigated single crystals parameter $k_F\xi \approx 100$ and thus phenomenologically NdCeCuO - system is in a range of Cooper-pair-based (BCS) superconductivity.

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1 Introduction

In the hole-doped cuprate high-$T_c$ superconductors the size of the pairs, as estimated from the Ginzburg-Landau coherence length $\xi$, is only few times the lattice spacing [1] in contrast to ordinary superconductors where the pair size greatly exceeds the lattice spacing or the average distance between carriers. In view of short coherence length of high-$T_c$ superconductors a situation close to compact bosons with Bose-Einstein (BE) condensation at $T_c$ is conceivable. The evolution from BCS superconductivity to BE condensation through the increase of the coupling strength between fermions was studied by Nozieres and Schmitt-Rink [2] and it was concluded that the evolution is smooth.

In [3] convenient phenomenological parameter was selected to establish the crossover from BCS superconductivity to BE condensation of composite bosons, namely, the product $k_F\xi$ of Fermi wave vector times the coherence length. Pistolesi et al. [3] argued that Cooper-pair-based superconductivity is stable against bosonization down to $k_F\xi = 2\pi$. The stabilization criterion $k_F\xi \geq 2\pi$ corresponding to the condition $\xi > \lambda_F$, with $\lambda_F = 2\pi/k_F$ being the electron wave length, should be regarded as an analog of the Ioffe-Regel criterion for transport in disordered systems [4].

It appears that for hole-doped high-$T_c$ superconductors (series of La-, Y-, Bi- and Tl-systems) $k_F\xi \approx 10$ that are although in a BCS range but near the ”instability” line $k_F\xi = 2\pi$ on the plot of $T_c$ vs $T_F (= E_F/k)$ of Uemura et al. [5]. Our goal was to estimate a parameter $k_F\xi$ at electron-doped superconductor Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$ with various Ce concentration.

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2 Experimental results and discussion

In order to find $\xi$ the low-temperature measurements of upper critical field $B_{c2}$ on Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$ single crystal films with various Ce concentration and nonstoichiometric disorder $\delta$ [8] in magnetic fields up to 9T ($B \parallel c$, $J \parallel ab$) and temperature range 0.4-40 K with SQUID-magnitometer MPMS XL of Quantum Design and by dc-current method in solenoid up to 12T from “Oxford Instruments” were carried out.

In Fig.1 the dependencies of the resistivity $\rho$ in CuO$_2$ planes ($J \parallel ab$) on perpendicular magnetic field $B \parallel c$ are presented for optimally reduced films with $x = 0.14; 0.15; 0.18; 0.20$ and an example of $B_{c2}$ determination (for $x = 0.15$ at $T = 0.4$ K) is shown. As it should be obtained $B_{c2}$ value is the higest for optimally doped sample with with $x = 0.15$.

Fig.2 demonstrates an effect of nonstoichiometric disorder on the upper critical field of optimally doped Nd$_{1.85}$Ce$_{0.15}$CuO$_{4+\delta}$ system. Results of magnetoresistance measurement are presented for three types of Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$ single crystal films [7]: as-grown samples, optimally reduced samples (optimally annealed in a vacuum at $T = 780^\circ$ C for $t = 60$ min; $p = 10^{-2}$ mmHg) and non optimally reduced samples (annealed in a vacuum $T = 780^\circ$ C for $t = 40$ min; $p = 10^{-2}$ mmHg). The film thickness was 1200 - 2000 Å.

Using the relation between the coherence length and the upper critical field $2\pi B_{c2}\xi^2 = \Phi_0$ where the elementary flux quantum $\Phi_0 = \pi e \hbar / c$, the values of $\xi$ for all samples were estimated. The data for normal state in-plane resistivity and Hall coefficient [6] were turned into account for determination of parameter $k_F \ell$, mean free path $\ell$ and $k_F = (2\pi n_s)^{1/2}$, $n_s$ being the surface electron density. All the obtained parameters along with the $k_F \xi$ values are presented in Table 1 for optimally reduced samples with different Ce concentration and in Table 2 for samples with $x = 0.15$ and different nonstoichiometric disorder. It is known [8] that for “dirty” ($\ell < \xi$) s-wave superconductor

$$B_{c2}(T = 0) = \frac{1}{2\gamma} \cdot \frac{\Phi_0}{\hbar D} \cdot kT_c$$

where constant $\gamma \cong 1.78$, $D = v_F \ell / 2 = \frac{\hbar}{2m}k_F \ell$ is the diffusion coefficient, $v_F$ is Fermi velocity.

Then

$$\xi = \sqrt{\xi_0 \ell},$$

where $\xi_0 \cong \frac{\hbar v_F}{kT_c}$ is the coherence length in pure superconductor. From (1) and (2) we have $B_{c2} \sim (k_F \ell)^{-1}$ and $\xi \sim \sqrt{k_F T_c}$, thus $B_{c2}$ should increase and $\xi$ should decrease with increase of $(k_F \ell)^{-1}$ as a degree of disorder.

As it is seen from Table 2 for Nd$_{1.85}$Ce$_{0.15}$CuO$_{4+\delta}$ the upper critical field quickly decreases and the coherence length increases with increasing of degree of disorder (parameter $(k_F \ell)^{-1}$) in contradiction with standard results for s-wave superconductor. Such an unusual behavior of $B_{c2}$ and $\xi$ with variation of disorder may be an evidence of d-wave symmetry of superconducting order parameter for Nd$_{1.85}$Ce$_{0.15}$CuO$_{4+\delta}$. It is in accordance with the theoretical considerations of Yin and Maki [9] for d-wave superconductors as with our results for a slope of upper critical field in vicinity of $T_c$ in this electron doped system [10].

In Fig.3 a log-log plot of $T_c$ versus Fermi temperature $T_F = \varepsilon_F / k$ (so named “Uemura plot” [5]) for different superconductors is presented and the points for Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$ system received by us are also shown. The lines with constant $k_F \xi$ values ($k_F \xi = 2\pi$ and $k_F \xi = 10^8$, $n = 1 \div 5$) are superimposed on the plot according to [8]. It may be seen that parameter $k_F \xi \cong 100$ for different samples of single crystals Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$ with various Ce concentration and nonstoichiometric disorder. Thus this electron doped system is even more deep in the region of BCS-coupling than hole-doped cuprate systems. The value of $k_F \xi$
is minimal for optimally doped system \( (k_F\xi = 70\div80 \) and nearly independent on a degree of disorder) and increases for overdoped \((x = 0.18 \) and \(0.20)\) samples.

3 Conclusions

Thus, from a values of upper critical field we estimate the coherence length in Nd\(_{2-x}\)Ce\(_x\)CuO\(_{4+\delta}\) system with various \(x\) and \(\delta\). Then, using the universal (independent of the details of the interaction potential) phenomenological parameter \(k_F\xi \)\[^3\], we illustrate that investigated electron doped cuprate NdCeCuO system doesn’t cross the instability line of BCS superconductivity \(k_F\xi = 2\pi\) even for optimally doped and optimally reduced samples.

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Table 1

Table 1: The data for Nd$_{2-x}$Ce$_x$CuO$_4$ optimally reduced films.

| Samples | $T_c$, K | $B_{c2}$, T | $k_F\ell$ | $\xi$, Å | $k_F\xi$ |
|---------|----------|-------------|-----------|-----------|-----------|
| x=0.14  | 11       | 2.9         | 2.7       | 106.5     | -         |
| x=0.15  | 21       | 6.1         | 51.6      | 73.5      | 74.2      |
| x=0.18  | 6        | 0.76        | 44.4      | 207.7     | 118.4     |
| x=0.20  | <1.3     | 0.4         | 14.6      | 273.3     | 166.7     |

Table 2

Table 2: The data for Nd$_{1.85}$Ce$_{0.15}$CuO$_{4+\delta}$ films with different nonstoichiometric disorder.

| Samples                | $B_{c2}$, T | $k_F\ell$ | $\ell$, Å | $\xi$, Å | $k_F\xi$ |
|------------------------|-------------|-----------|-----------|-----------|-----------|
| Optimally reduced      | 6.1         | 51.6      | 51.3      | 73.5      | 74.2      |
| Non optimally reduced  | 4.8         | 9.1       | 12.5      | 82.3      | 68.3      |
| As grown               | 1.3         | 8.6       | 13.4      | 158.7     | 80.9      |
Figure 1: Resistivity at CuO$_2$-planes ($J \parallel ab$) vs magnetic field ($B \parallel c$) for samples Nd$_{2-x}$Ce$_x$CuO$_4$ with different Ce concentration at low temperatures. The lines are guides to the eye.
Figure 2: Resistivity at CuO$_2$-planes ($J \parallel ab$) vs magnetic field ($B \parallel c$) for samples Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ with different nonstoichiometric disorder at $T = 2$ K.
Figure 3: “Uemura plot” with constant $k_F\xi$ lines and with our points for Nd$_{2-x}$Ce$_x$CuO$_{4+\delta}$ system.