Fizika Nizkikh Temperatur, 2011, v. 37, No. 4, p. 377–379

The estimation of coherence length for electron-doped superconductor $Nd_{2-x}Ce_xCuO_{4+\delta}$

T.B. Charikova, G.I. Harus, N.G. Shelushinina, and O.E. Sochinskaya

Institute of Metal Physics RAS, Ekaterinburg, Russia
E-mail: charikova@imp.uran.ru

A.A. Ivanov

Moscow Engineering Physics Institute, Moscow, Russia

Received September 24, 2010

Results of low-temperature upper critical field measurements for $Nd_{2-x}Ce_xCuO_{4+\delta}$ single crystals with various x and nonstoichiometric disorder (δ) are presented. The coherence length of pair correlation ξ 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 $k_F\xi \cong 100$ and thus phenomenologically NdCeCuO-system is in a range of Cooper-pair-based (BCS) superconductivity.

PACS: 74.25.F– Transport properties;
74.72.–h Cuprate superconductors.

Keywords: single crystals, electron-doped superconductor, Fermi wave vector.

1. Introduction

In the hole-doped cuprate high-T_c superconductors the size of the pairs, as estimated from the Ginzburg–Landau coherence length ξ, 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) $k_F\xi \cong 10$ 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 $Nd_{2-x}Ce_xCuO_{4+\delta}$ with various Ce concentration.

2. Experimental results and discussion

In order to find ξ the low-temperature measurements of upper critical field B_{c2} on $Nd_{2-x}Ce_xCuO_{4+\delta}$ single crystal films with various Ce concentration and nonstoichiometric disorder δ [6] in magnetic fields up to 9 T ($B \parallel c$, $J \parallel ab$) 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 ρ 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 $x = 0.15$.

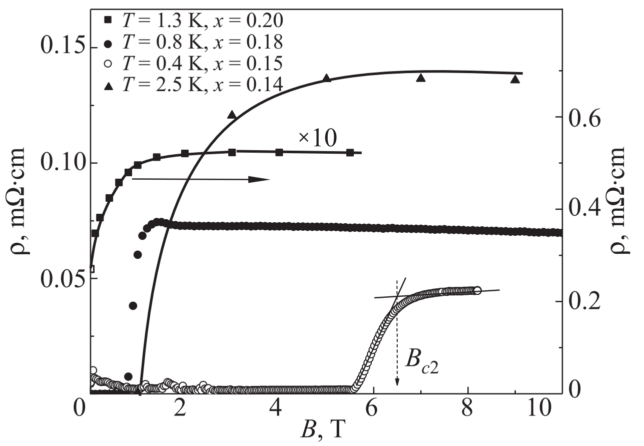

Fig. 1. Resistivity at CuO_2-planes ($J \parallel ab$) vs magnetic field ($B \parallel c$) for samples $Nd_{2-x}Ce_xCuO_4$ with different Ce concentration at low temperatures. The lines are guides to the eye.

Figure 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 $Nd_{2-x}Ce_xCuO_{4+\delta}$ single crystal films [7]: as-grown samples, optimally reduced samples (optimally annealed in a vacuum at $T = 780$ °C for $t = 60$ min; $p = 10^{-2}$ mm Hg) and non optimally reduced samples (annealed in a vacuum $T = 780$ °C for $t = 40$ min; $p = 10^{-2}$ mm Hg). The film thikness 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 $\Phi_0 = \pi c\hbar/e$, the values of ξ for all samples were estimated. The data for normal state in-plane resistivity and Hall coefficient [6] were turned to account for determination of parameter $k_F\ell$, mean free path ℓ 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.

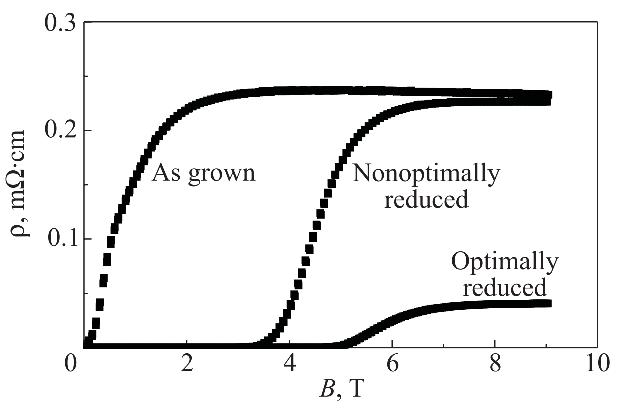

Fig. 2. Resistivity at CuO_2-planes ($J \parallel ab$) vs magnetic field ($B \parallel c$) for samples $Nd_{1.85}Ce_{0.15}CuO_4$ with different nonstoichiometric disorder at $T = 2$ K.

Table 1. The data for $Nd_{2-x}Ce_xCuO_4$ optimally reduced films

Samples	T_c, K	B_{c2}, T	$k_F\ell$	ξ, 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. The data for $Nd_{1.85}Ce_{0.15}CuO_{4+\delta}$ films with different nonstoichiometric disorder

Samples	B_{c2}, T	$k_F\ell$	ℓ, Å	ξ, Å	$k_F\xi$
Optimally reduced	6.1	51.6	51.3	73.5	74.2
Nonoptimally reduced	4.8	9.1	12.5	82.3	68.3
As grown	1.3	8.6	13.4	158.7	80.9

It is known [8] that for “dirty” ($\ell < \xi$) *s*-wave superconductor

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

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

$$\xi = \sqrt{\xi_0\ell}, \quad (2)$$

where $\xi_0 \cong \hbar v_F/(kT_c)$ is the coherence length in pure superconductor. From (1) and (2) we have $B_{c2} \sim (k_F\ell)^{-1}$ and $\xi \sim \sqrt{k_F\ell}$, thus B_{c2} should *increase* and ξ 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 ξ with variation of disorder may be an evidence of *d*-wave symmetry of superconducting order parameter for $Nd_{1.85}Ce_{0.15}CuO_{4+\delta}$ system. It is in accordance with our results for a slope of upper critical field in vicinity of T_c for this electron doped superconductor [9].

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 $Nd_{2-x}Ce_xCuO_{4+\delta}$ system received by us are also shown. The lines with constant $k_F\xi$ values ($k_F\xi = 2\pi$ and $k_F\xi = 10^n$, $n = 1$–5) are superimposed on the plot according to [3]. It may be seen that parameter $k_F\xi \cong 100$ for different samples of single crystals $Nd_{2-x}Ce_xCuO_{4+\delta}$ 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 ($k_F\xi = 70$–80 and nearly independent on a degree of dis-

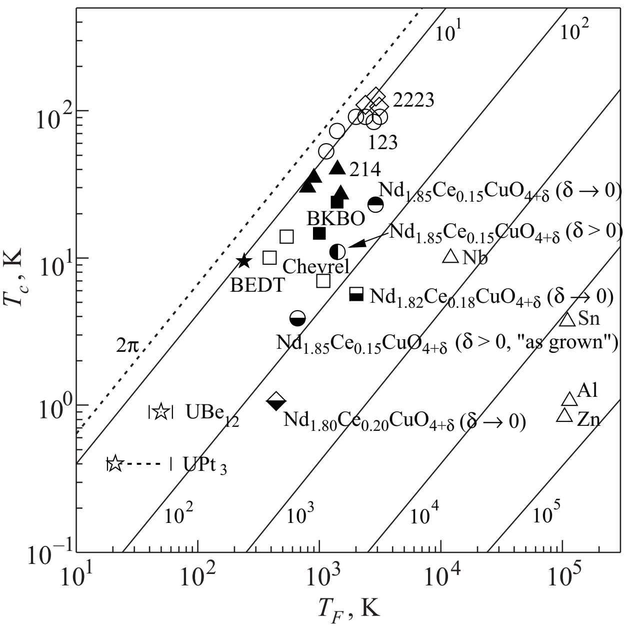

Fig. 3. "Uemura plot" [5] with constant $k_F\xi$ lines [3] and with our points for $Nd_{2-x}Ce_xCuO_4$ system.

order) 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 $Nd_{2-x}Ce_xCuO_{4+\delta}$ system with various x and δ. 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.

We are grateful to V.N. Neverov for experimental support. This work was done within RAS Programm (project N 01.2.006.13394).

1. M. Randeria, in: *Bose-Einstein Condensation,* Cambrige Univ. Press, 355 (1995).
2. P. Nozieres and S. Schmitt-Rink, *J. Low. Temp. Phys.* **59**, 195 (1985).
3. F. Pistolesi and G.C. Strinati, *Phys. Rev.* **B49**, 6356 (1994).
4. N.F. Mott and E.A. Davis, *Electronic Processes in Non-Crystalline Materials*, Mir, Moscow (1974).
5. Y.J. Uemura, L.P. Le, G.M. Luke, B.J. Sternlieb, W.D. Wu, J.H. Brewer, T.M. Riseman, C.L. Seaman, M.B. Maple, M. Ischikawa, D.G. Hinks, J.D. Jorgensen, G. Saito, and H. Yamochi, *Phys. Rev. Lett.* **66**, 2665 (1991).
6. T.B. Charikova, A.I. Ponomarev, G.I. Kharus, N.G. Shelushinina, A.O. Tashlykov, A.V. Tkach, and A.A. Ivanov, *JETP* **105**, 626 (2007).
7. A.A. Ivanov, S.G. Galkin, A.V. Kuznetsov, and A.P. Menushenkov, *Physica* **C180**, 69 (1991).
8. P.G. de Gennes, *Superconductivity of Metals and Alloys*, Mir, Moscow (1968).
9. T.B. Charikova, N.G. Shelushinina, G.I. Kharus, and A.A. Ivanov, *JETP Lett.* **88**, 123 (2008).