Temperature dependence of coherence lengths for optimally-doped $YBa_2Cu_3O_{7-\delta}$ thin films

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It is believed that understanding the mechanisms of electron pairing in high-temperature superconductors (HTSCs) will indicate the direction of synthesis of superconductors with a desired high T_c.

Upper critical field $\mu_0H_{c2}(T)$ is a fundamental measure of the strength of superconductivity. However, despite the recent breakthrough in achieving extremely strong magnetic fields, there is still no consensus on the exact value of $\mu_0H_{c2}(0)$ for optimally doped $YBa_2Cu_3O_{7-\delta}$-samples due to the complexity of the experimental procedures. All this leads to a large error at low temperatures near 0 K, and especially when measuring in pulsed fields. Because of this obstacle, the chances of accurately determining the upper critical magnetic field in other cuprate HTSCs with even higher T_c are also greatly reduced.

Having measured the superconducting (SC) transition curves of the sample in various magnetic fields and using the special software, we calculated the upper critical fields $\mu_0H_{c2}(0)$ of the optimally doped YBCO film both within the Ginzburg-Landau (GL) [1,2] and Werthamer-Helfand-Hochenberg (WHH) [3] theories. As a result, it was possible to reconstruct and plot complete curves $\mu_0H_{c2}(T)$. The calculations were carried out for orientations of the external magnetic field parallel to both the ab-plane and the c-axis. We note a significant difference between the results obtained depending on the theory under consideration. The results obtained made it possible for the first time to calculate the temperature dependences of the coherence lengths in the ab-plane ξ_{ab} and along the c-axis ξ_c.

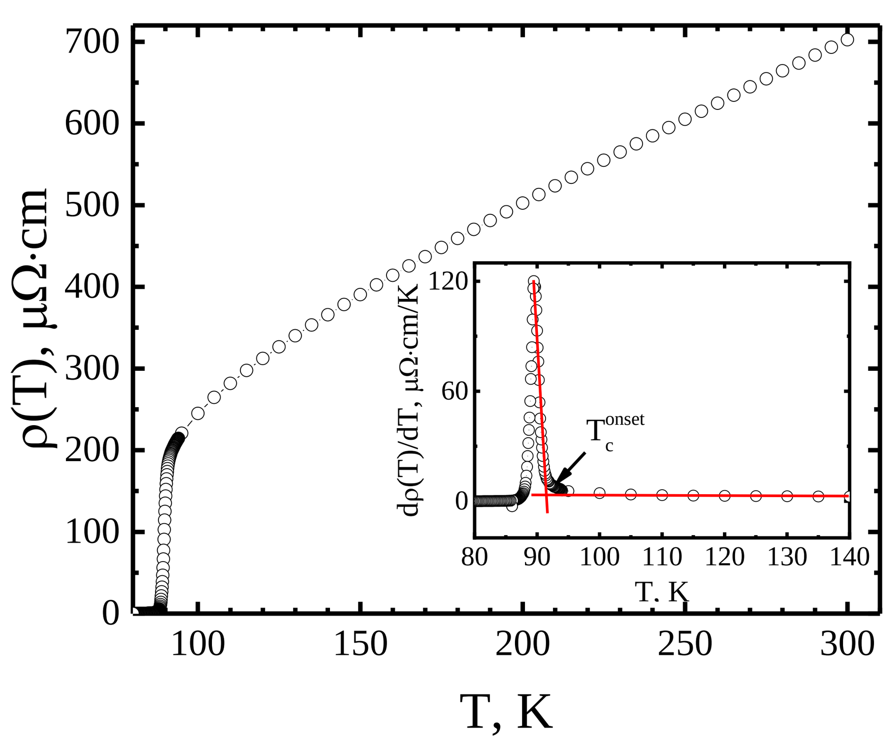

Fig.1. Temperature dependence of the resistivity $\rho(T) = \rho_{ab}(T)$ of the $YBa_2Cu_3O_{7-\delta}$ film in the range 80-300 K in the absence of the external magnetic field. Inset represents a derivative of $\rho(T)$ at $H = 0$. The intersection of red straight lines defines T_c^{on}.

The main measurements of YBCO films were performed using a fully computerized setup, including a Quantum Design Physical Property Measurement System (PPMS-9), using a drive current of ~100 μA at 19 Hz. The four-probe technique was used to measure the in-plane resistivity $\rho_{ab}(T) = \rho(T)$. During cooling, a constant magnetic field from zero to 9 T was sequentially applied to the sample to measure superconducting transitions.

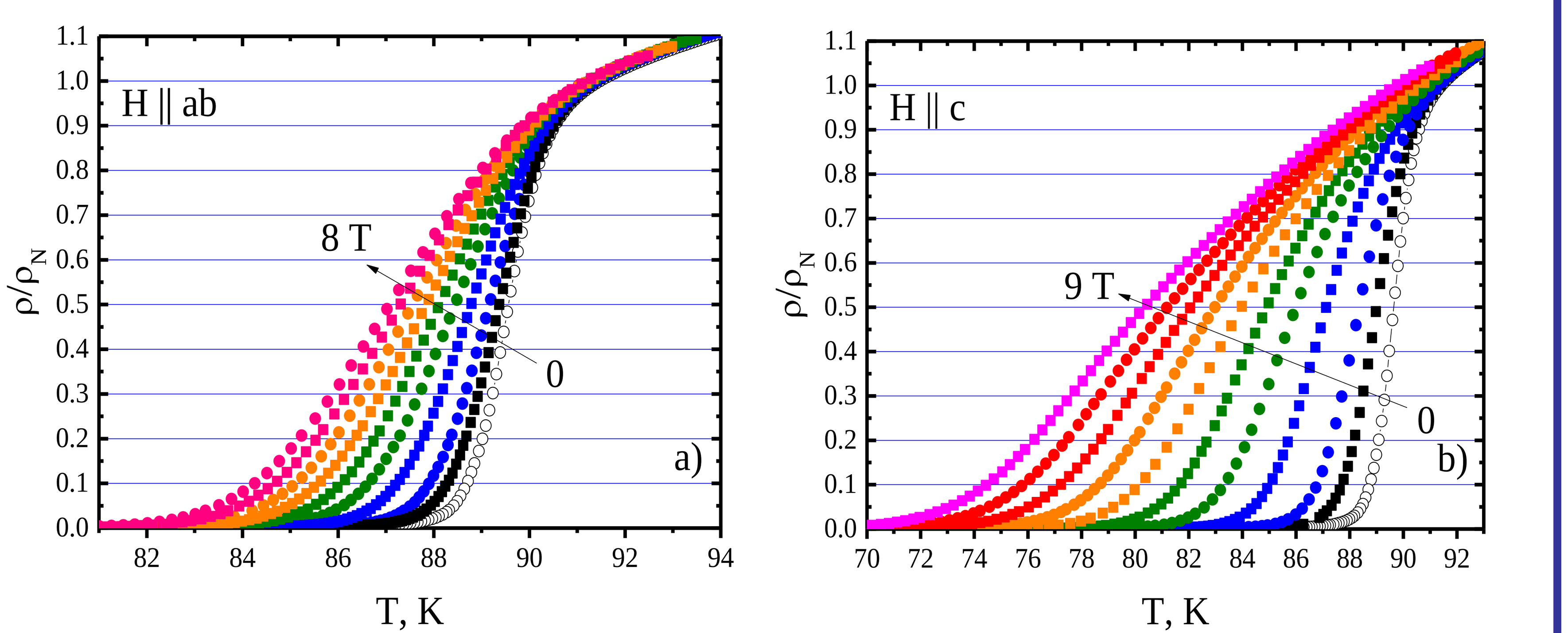

Fig.2. Temperature and magnetic field dependences of $\rho(T,H)$ in units of (ρ/ρ_N) of the $YBa_2Cu_3O_{7-\delta}$ film. Fig. 2a and Fig. 2b are obtained for the field orientations, parallel ($H \parallel ab$, μ_0H = 0, 0.5, 1, 2, 3, 4, 5, 6, 7 and 8 T) and perpendicular ($H \parallel c$, μ_0H = 0, 0.5, 1, 2, 3, 4, 5, 6, 7, 8 and 9 T) to the *ab*-plane, respectively.

To calculate the temperature dependences of upper critical fields $\mu_0H_{c2}(T)$ for H || ab and H || c for the YBCO thin film under study, the data of Fig. 2a and 2b were used, respectively.

$$\ln\frac{1}{t}=\left(\frac{1}{2}+\frac{i\lambda_{so}}{4\gamma}\right)\psi\left(\frac{1}{2}+\frac{\bar{h}+\frac{1}{2}\lambda_{so}+i\gamma}{2t}\right)+\left(\frac{1}{2}-\frac{i\lambda_{so}}{4\gamma}\right)\psi\left(\frac{1}{2}+\frac{\bar{h}+\frac{1}{2}\lambda_{so}-i\gamma}{2t}\right)-\psi\left(\frac{1}{2}\right)(1);\gamma\equiv\left[\left((\alpha\bar{h})^2-\left(\frac{1}{2}\lambda_{so}\right)^2\right)\right]^{\frac{1}{2}}(2);\ h^*=-\frac{H_{c2}}{(dH_{c2}/dt)\big|_{t=1}}=(\pi^2/4)\bar{h}\quad(3)$$

Formulas 1-3 written in the Mathcad 12.0 environment were used for the analysis, taking the Maki parameter α and the spin–orbit scattering parameter λ_{so} as fitting parameters within the WHH theory.

The formula from the GL theory looks as follows:

$$H_{c2}(T)=\frac{\phi_0}{2\pi\xi^2(T)}=H_{c2}(0)\cdot\frac{(1-t^2)}{(1+t^2)}\quad(4)$$

where, as before, $t = T/T_c$ and $\Phi_0 = 2.068\cdot10^{-15}$ T·m² is the magnetic flux quantum.

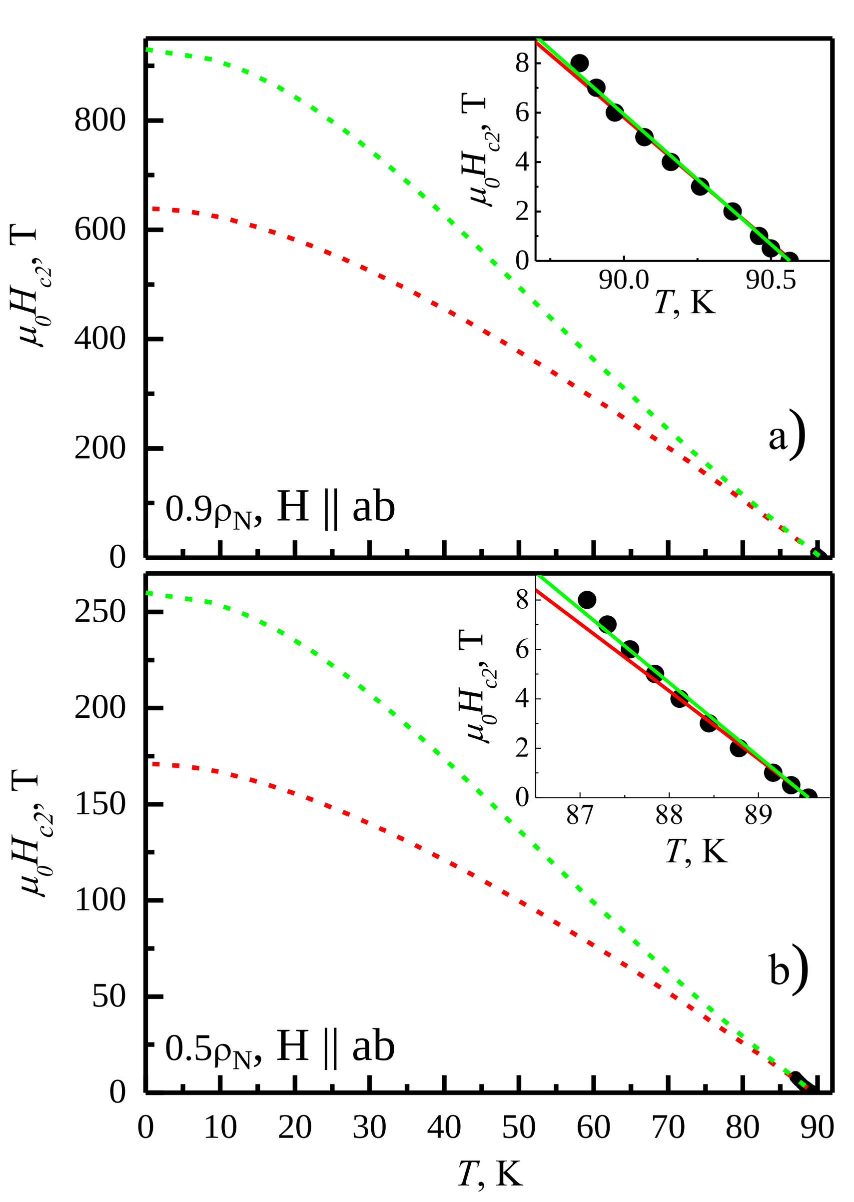

Fig.3. Temperature dependences of the upper critical magnetic fields $\mu_0H_{c2}(T) \parallel ab$ determined at $\rho = 0.9\rho_N$ (a) and $\rho = 0.5\rho_N$ (b).

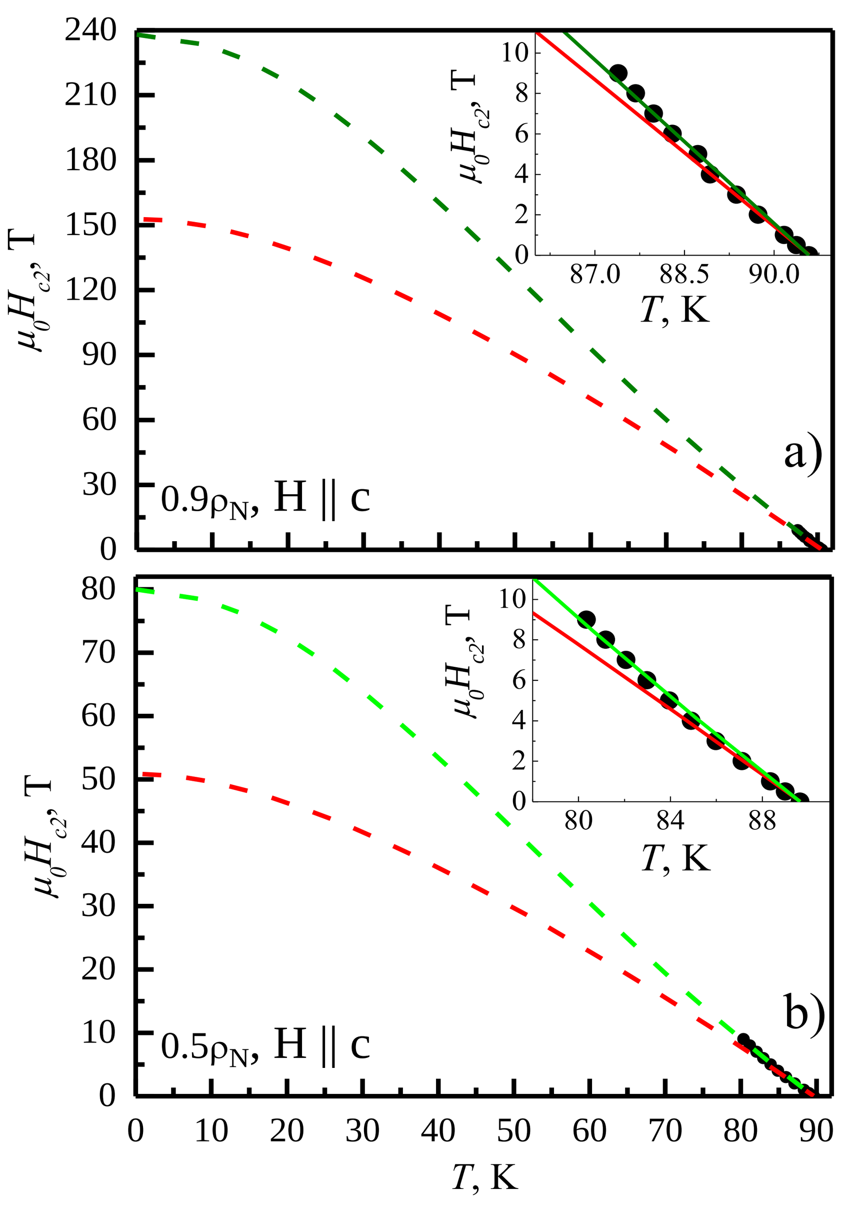

Fig.4. Temperature dependences of the upper critical magnetic fields $\mu_0H_{c2}(T) \parallel c$ determined at $\rho = 0.9\rho_N$ (a) and $\rho = 0.5\rho_N$ (b).

The red and green dashed curves represent the results of calculations within the WHH and Ginzburg-Landau theories, respectively. The insets show the same dependences in the vicinity of T_c^{on}, indicated by solid lines, and with larger experimental points.

Having determined the temperature dependences of the upper critical fields for various orientations of the magnetic field, one can calculate the corresponding dependences of the coherence lengths in the entire temperature range of interest using the following equations:

$$\xi_{ab}(T)=\sqrt{\frac{\Phi_0}{2\pi\mu_0H_{c2}(T)}},H\parallel c\quad(5);\qquad \xi_c(T)=\frac{\Phi_0}{2\pi\mu_0H_{c2}(T)\xi_{ab}(T)},H\parallel ab\quad(6)$$

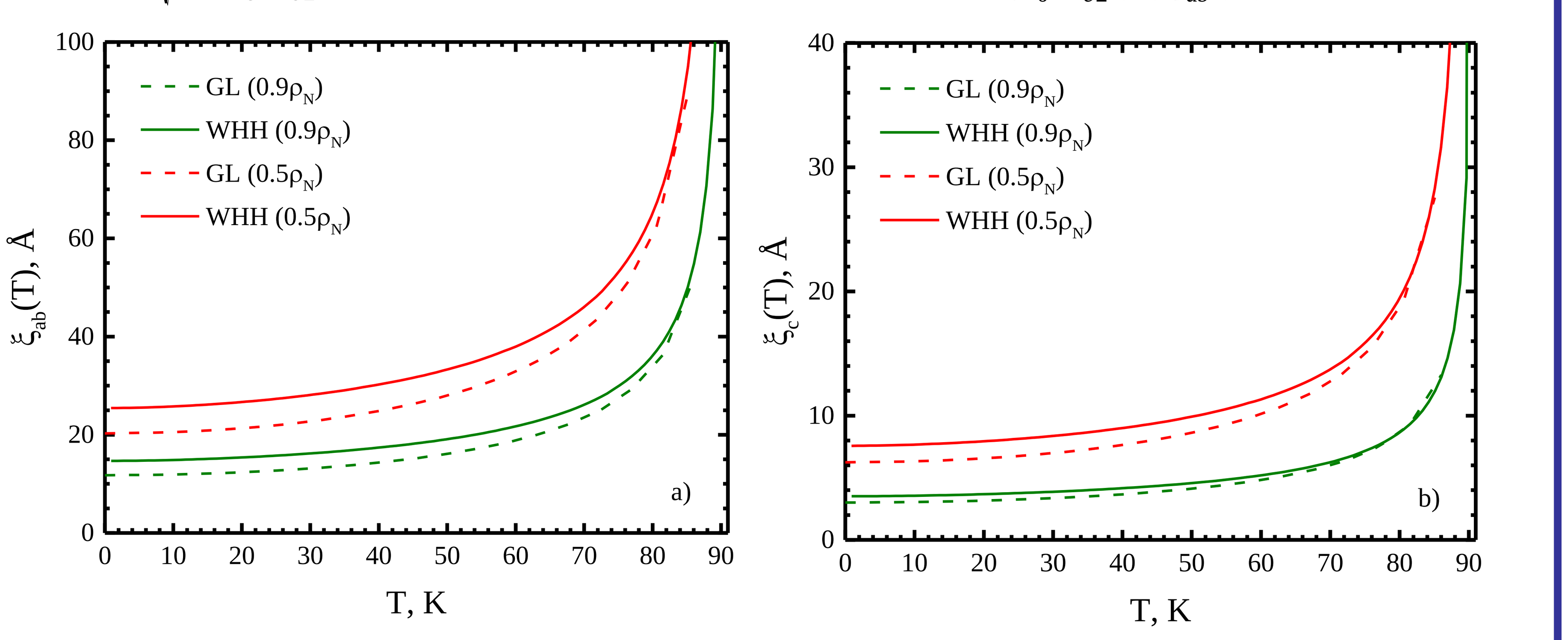

Fig.5. Temperature dependences of $\xi_{ab}(T)$ (*Fig. 5a*) and $\xi_c(T)$ (*Fig. 5b*) coherence lengths calculated from dependences $\mu_0H_{c2}(T)$, *H || ab* and $\mu_0H_{c2}(T)$, *H || c* (*Fig. 3 and 4*) using GL (dashed curves) and WHH (solid curves) theories. The criteria 0.9ρN (green curves) and 0.5ρN (red curves) are taken into account.

The results are represented in Fig. 5, using in equations (5) and (6) $\mu_0H_{c2}(T)$ found above for all four cases. The figure shows that, near T_c, the GL and WHH curves tend to coincide. At lower temperatures, the curves diverge, which is more pronounced when using the $0.5\rho_N$ criterion.

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