The in- and out-of-plane magnetisation of highly underdoped Y $Ba_2Cu_3O_{6+x}$ single crystals

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Background

In two recent papers [1,2] we have shown how measurements of static magnetic susceptibility $\chi_c(T)$ of $YBa_2Cu_3O_{6+x}$ single crystals for magnetic fields applied along the *c*-axis, and $\chi_{ab}(T)$ for fields in the *ab*-plane, can give useful information about their thermodynamic properties which are still being hotly debated. SQUID magnetometry above the superconducting (s/c) transition temperature T_c is used for larger crystals, while piezolever torque magnetometry gives $\chi_D(T) = \chi_c(T) - \chi_{ab}(T)$ for tiny crystals [2]. Here we present some new data for highly under-doped crystals with hole concentrations per CuO_2 plane p =0.058 to 0.073. This is the region where neutron scattering studies [3,4] give evidence for competition between incommensurate magnetic short-range order and superconductivity. We have studied crystals with three values of x, measuring $\chi_c(T)$ and $\chi_{ab}(T)$ immediately after fixing x by quenching on to a copper block and again after allowing sufficient time at room temperature for the Cu-O chains to order.

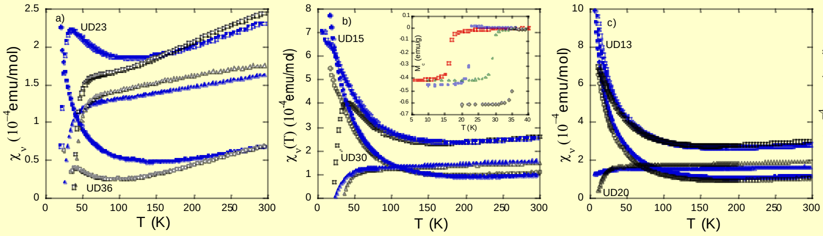


FIG. 1: (a) Temperature dependence the static magnetic susceptibility $\chi_c(T)$ and $\chi_{ab}(T)$ for H // the c axis and the ab plane respectively, together with the anisotropy $\chi_c(T) - \chi_{ab}(T)$ for six $YBa_2Cu_3O_{6+x}$ crystals studied in an applied magnetic field of 5 T. The inset to Fig. 1 (b) shows the superconducting transition of the $YBa_2Cu_3O_{6+x}$ crystals measured on warming in 10 Gauss using a Squid magnetometer after cooling in zero field.

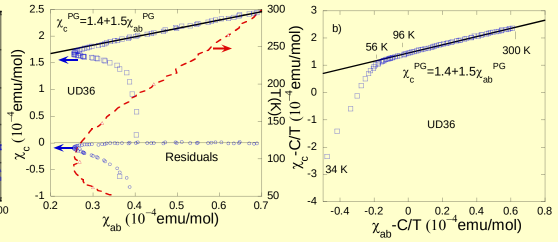


FIG. 3: (a) The static magnetic susceptibility $\chi_c(T)$ versus $\chi_{ab}(T)$ for H = 5 T // the c axis and the ab plane respectively, of $YBa_2Cu_3O_{6+x}$ single crystal UD36. The solid lines show linear fits. (b) The $\chi_c(T)$ − C/T versus $\chi_{ab}(T)$ − C/T for H = 5 T.

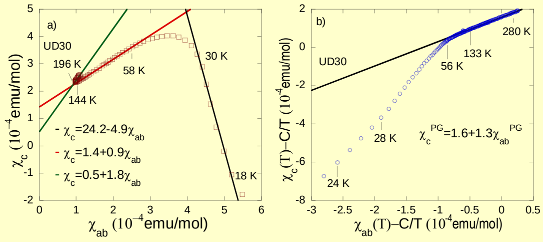


FIG. 2: (a) The static magnetic susceptibility $\chi_c(T)$ versus $\chi_{ab}(T)$ for H = 5 T k the c axis and the ab plane respectively, of $YBa_2Cu_3O_{6+x}$ single crystal UD30. The solid lines show linear fits. (b) The $\chi_c(T)$ − C/T versus $\chi_{ab}(T)$ − C/T for H = 5 T of UD30.

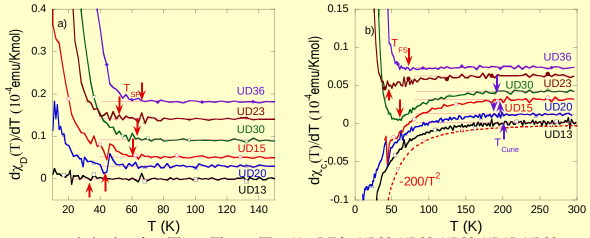


FIG. 4: (a) The temperature derivative of $\chi_D(T) = \chi_c(T) - \chi_{ab}(T)$ at H = 5 T for UD36, UD23, UD30, UD15, UD20 and UD13. (b) The temperature derivative of $\chi_c(T)$ for the same crystals . For clarity the data are shifted.

Analysis of the magnetic susceptibility data

$$\chi(T) = \chi_{PG}(T) + \chi_{FL}(T) + C/T + \chi_{VV}(T) + \chi_{core}(T) \quad (1)$$

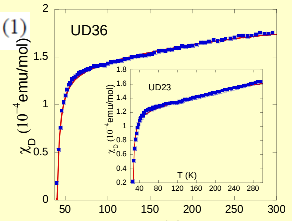
$$\chi_{PG}(T) = N_0\mu_B^2\left\{1 - \left(\frac{E_g}{2k_BT}\right)^{-1}\ln\left[\cosh\left(\frac{E_g}{2k_BT}\right)\right]\right\} \quad (2)$$

For $T<0.3\,E_g/k_B$, the limiting form is:

$$\chi_{PG}(T) = A\frac{2k_BT}{E_g}\ln 2$$

where $A=N_0\mu_B^2$.

$$M_c^{FL}(T) = -\frac{\pi k_B T H}{3\Phi_0^2}\frac{\xi_{ab}^2}{s\sqrt{1+(2\xi_{ab}/\gamma s)^2}} \quad (3)$$



Here $\gamma = \xi_{ab}/\xi_c$ is the anisotropy, $\xi_{ab} = \xi_{ab}(0)/e^{1/2}$ and $\xi_c = \xi_c(0)/\varepsilon^{1/2}$, $\varepsilon = \ln(T/T_c)$ are the T-dependent GL coherence lengths // and ⊥ to the layers, s = 1.17 nm is the distance between CuO_2 bi-layers, Φ_0 is the flux quantum for pairs and k_B is Boltzmann's constant. Eq. 4 is valid when $H \ll \Phi_0/(2\pi\xi_{ab}^2)$ and then the susceptibility $\chi_c^{FL} \equiv M_c^{FL}/H$ does not vary with H.
For H⊥c, χ_{ab}^{FL} =0 in the two-dimensional (2D) limit $s \gg \xi_c(T)$ and in the opposite 3D limit $\chi_{ab}^{FL} = |\chi_c^{FL}/g$. The solid line show the fit of Eq. 1 to the magnetic susceptibility data of the UD36 and UD23 crystals.

x meas	T_c (K)	10^4C $\frac{emuK}{mole}$	10^4A $\frac{emu}{mole}$	$10^4\chi_0$ $\frac{emu}{mole}$	T_{PG} (K)	ξ_{ab} (nm)	p $/CuO_2$
0.42	36.2	28.1±1	1.49	1.52	739	3.51	0.073
0.40	30.1	160.7±3	1.50	1.43	770	4.22	0.069
0.42	23.3	49.5±2	1.86	1.34	796	4.15	0.064
0.37	20.2	150.2±3	1.42	1.59	802	5.28	0.063
0.40	15.7	200.4±3	1.45	1.45	821	6.1	0.060
0.37	13.0	165.3±3	1.55	1.32	833	7.51	0.058

TABLE I: Summary of results. The x values in the first column are determined form weight loss on annealing and thermogravimetric analysis in flowing argon for the present crystals. The critical temperature T_c was taken as the midpoint of the superconducting transition, as determined by measuring the field-warming magnetisation at 10 Oe after zero-field cooling. C, A, $\chi_0 = \chi_{VV} + \chi_{core}$ and ξ_{ab} are the parameters of Eq. 1 of fit to the magnetic susceptibility data shown in Fig. 1. The T_{PG} is the psudogap temperature. The values of p are obtained from Ref.6.

Conclusion

The main results of this work are:
(i) The T-dependent anisotropy well above T_c arises from the pseudogap and the g-factor anisotropy.
(ii) At lower T, there are Gaussian s/c fluctuations.
(iii) For all six crystals the $\chi_D(T)$ has a weakly T-dependent linear region at higher T.
(iv) Isotropic Curie contribution to $\chi(T)$ with the onset temperature below 200 K.
(v) Ordering the CuO chains reduces the Curie contribution to $\chi(T)$

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