New magnetic field scaling of NMR in cuprates

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Abstract

The magnetic field dependence of the low temperature specific heat coefficient $\gamma(T,H) = C(T,H)/T$ has been shown experimentally and theoretically to obey the scaling relation $\gamma(T,H) = \gamma_0\sqrt{T^2 + Ah}$, where $h = |H|/1\mathrm{T}$ and the coefficient A depends upon field direction. This suggests that also other quantities such as the NMR Knight shifts $K_\alpha(T,h)$ $(\alpha = c, ab)$ and the relaxation rates $w_\alpha(T,h) = (T_1T)^{-1}$ may be expressed in terms of the scaled variable $\overline{T} = \sqrt{T^2 + A_\alpha h}$ in the form $K_\alpha(T,h) = K_0(\overline{T})$ and $w_\alpha(T,h) = w_0(\overline{T})$, where the presence of vorteces in the mixed state simply rises the effective temperature $\overline{T}$. We have tested this idea using the recent NMR rate data on $TlSr_2CaCu_2O_{6.8}$ by G.-q. Zheng *et al* with $H||c$. The theoretical curve for $w(T,0)$ consists of a fermion part with added stripe contribution due to the localized triplet bosons. The data points for various field collapse to the curve $w(T,0)$, with $A = 80\ \mathrm{K}^2$.

Key words: superconductivity; NMR; stripes

The low temperature specific heat coefficient in $YBa_2Cu_3O_7$ has been shown by Wang *et al* [1] to satisfy the scaling relation

$$\frac{\gamma(T,H)}{T} = \gamma_0\sqrt{1+z^2}\,, \tag{1}$$

where $z = A^{1/2}h^{1/2}/T$ in the scaled variable with A and γ_0 parameters. The function $\sqrt{1+z^2}$ was used as an interpolation function between the limits $h = 0$ and $T = 0$, which according to the d-wave model [2] are $\gamma(T,0) \sim T$ and $\gamma(T,h)/T \sim \sqrt{h}$ in the case of $H||c$. Subsequently it was shown that the interpolating function actually follows from the chemical equilibrium theory [3] where the specific heat coefficient can be calculated from

$$\gamma(T,h) = \gamma[1 - f(T,H)] = \gamma[1 + \frac{\alpha}{t^2 + \beta_1 h}]^{-1/2}\,, \tag{2}$$

with $t = T/T^*$. Since the value of β_1 obtained was small $\beta_1 \approx .0056$, Eq.(2) reduces to Eq.(1) for small t, with $A = \beta_1 T^{*2}$ and $\gamma_0 = \gamma/\sqrt{\alpha}$. Here function $1 - f$ gives the fraction of fermions as a function temperature and magnetic field originally obtained at high temperatures for the chemical equilibrium reaction $B^{++} \rightleftharpoons 2h^+$ [3,4] with quadratic magnetic field dependence. The linear field dependence is due to presence of vorteces. The Eq.(2) suggests that function $f(T,h)$ can be written simply in terms of the effective temperature $\overline{T} = \sqrt{T^2 + A\,h}$ in the form $f(T,h) = f(\overline{T})$. To test whether this idea would work also for quantities other than the low temperature specific heat we have applied it to the NMR measurements of Zheng *et al* [5] on $TlSr_2CaCu_2O_{6.8}$ in magnetic fields ranging from 0 to 28 T. The Knight shifts $K_s(T,h)$ and the relaxation rates $w(T,h) = (T_{1c}T)^{-1}$ can be written in terms of the effective temperature $\overline{T}$ in the form

$$K_s(T,h) = K_0(\overline{T}) \tag{3}$$

$$w(T,h) = w_0(\overline{T})\,. \tag{4}$$

Notably this test can be done without knowing explicitely the functions K_0 and w_0. Due to the uncertainties in the diamagnetic corrections for K_0 we have used only the rate data and the results are shown in Fig.1, which contains the measured points for the highest field $h = 28$ (black dots) and the mapping to the

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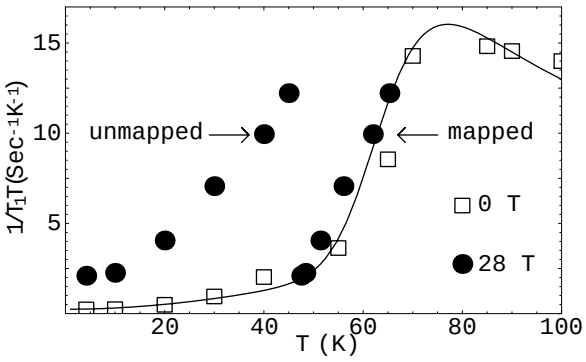

Fig. 1. Temperatur and magnetic field dependencies of $1/T_1T$. The line is calculated by using Eq.5. The experimental points are from Ref. [5] for ^{63}Cu.

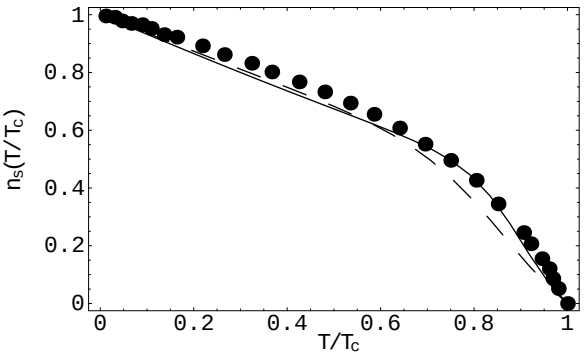

Fig. 2. Theoretical superfluid fraction $n_s(T)$ vs T/T_c for $YBa_2Cu_3O_{6.95}$ (T_c = 93.5 K, T^* = 170 K, T_0 = 83 K, and b = 5 K). Dashed line is calculateted for $TlSr_2CaCu_2O_{6.8}$ (T_c = 68 K, T^* = 120 K, T_0 = 60 K, and b = 6). The experimental points are from Ref. [7] for $YBa_2Cu_3O_{6.95}$.

curve $w_0(T)$. Although not shown in Fig.1, the smaller field points get also mapped to the same curve $w_0(T)$ to within the same accuracy.

We have also calculated the curve $w_0(T)$ by using the expression [4]

$$w_0(T) = C_0 + C_1[1 - f(T)]^2 + C_2[1 - \xi(T)]^2 f^2(T)\,, \quad (5)$$

where $[1-\xi(T)]f(T)$ gives the fraction of triplet bosons localized on CuO_6 octahedra, which is the present model for the stripes of localized charge and magnetic moment. The fact that the localized bosons have spin unity is due to the Hund's rule since the localization sites (CuO_5 or CuO_6) are chemical complexes. Within each CuO_2 plane the magnetic moments may have antiferromagnetic ordering. The first constant term in Eq.(5) is due to impurities and/or spectators, the second term from the holes and the third term from localized bosons. Above the temperature T_{BL}, all bosons are localized. Above this temperature $\xi = 0$ and the third term gives Curie-Weiss form. Besides this antiferromagnetic fluctuation term it also explains the spin gap effect. The parameter values used are $\alpha = .8$, $T^* = 130$ K, $C_0 = .24$ s^{-1}K^{-1}, $C_1 = 9.5$ s^{-1}K^{-1} and $C_2 = 72.1$ s^{-1}K^{-1}. We have used for the function $\xi(T)$ the fermi form $\xi(T) = (1 + \exp\frac{T-T_0}{b})^{-1}$ with $T_0 = 60$ K and $b = 6$ K. This looks like lots of parameters, but one can calculate now the outcome of most experiments in the normal state and the superfluid state. Good example is the superfluid fraction $n_s(T)$. Since the condensate is depleted by localization and by phonon scattering one obtains by the two fluid model

$$n_s(T) = \xi(T)f(T) - \xi(T_c)f(T_c)\left(\frac{T}{T_c}\right)^4 . \quad (6)$$

This expression has been used to calculate the superfluid fractions in Fig.2. The agreement in $YBa_2Cu_3O_{6.95}$ is very good. Clearly this expression can be used to calculate also $n_s(T, h)$.

Within the accuracy of the NMR experiments, $w(T, h)$ shows no magnetics field dependence in the normal state [6]. This is in agreement with the measurements of Gorny *et al* [6] on two compounds of YBCO. For the optimally doped compound with $T_c = 93$ K we obtain the mapping parameter $A \approx 82$ K^2, close to the value obtained for the thallium compound. The accuracy of the mapping is difficult to test because the low T values are missing.

The mapping can be used to calculate the upper critical field $h_{c2}(T)$ by setting $\overline{T} = T_c(0)$ and $T = T_c(h)$ to give

$$h_{c2}(T) = \frac{T_c(0)^2}{A}(1 - \tau^2)\,, \quad (7)$$

where $\tau = T/T_c(0)$. This curve is linear near $\tau \approx 1$ and gives $H_{c2}(0) \approx 58$ T.

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