Avoided Quantum Criticality in YBa$_2$Cu$_3$O$_y$ and La$_{2-x}$Sr$_x$CuO$_4$

J.E. Sonier, F.D. Callaghan, Y. Ando, R.F. Kiefl, J.H. Brewer, C.V. Kaiser, V. Pacradouni, S.-A. Sabok-Sayr, X.F. Sun, S. Komiya, W.N. Hardy, D.A. Bonn, and R. Liang

1 Department of Physics, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada
2 Canadian Institute for Advanced Research, 180 Dundas Street West, Toronto, Ontario M5G 1Z8, Canada
3 Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada
4 Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

(Dated: June 28, 2018)

Spin-glass (SG) magnetism confined to individual weakly interacting vortices is detected in two different families of high-transition-temperature ($T_c$) superconductors, but only in samples on the low-doping side of the low-temperature normal state metal-insulator crossover (MIC). Our findings unravel the mystery of the MIC, but more importantly identify the true location of the field-induced quantum phase transition (QPT) in the superconducting (SC) state. The non-uniform appearance of magnetism in the vortex state favors a surprisingly exotic phase diagram, in which spatially inhomogeneous competing order is stabilized at the QPT, and an ‘avoided’ quantum critical point (QCP) is realized at zero magnetic field.

PACS numbers: 74.72.-h, 74.25.Ha, 74.25.Qt, 76.75.+i

For nearly two decades, arrival at a firm theory for high-$T_c$ superconductivity has been hindered by an incomplete characterization of the phase diagram for doped copper oxides. Zero-field (ZF) muon spin rotation ($\mu$SR) and neutron scattering studies of magnetism in pure and Zn-doped La$_{2-x}$Sr$_x$CuO$_4$, point to the possible existence of a QCP under the SC ‘dome’ — corresponding to a zero-temperature phase transition at which a competing order is stabilized, and about which unusual properties emerge. The ZF-$\mu$SR measurements of Refs. [1, 2] support the occurrence of a QCP at what has been argued [3] to be a universal critical doping concentration $p_c \approx 0.19$, whereas the neutron studies [4] suggest there is a QCP near $p_c = 0.125$.

It is now well established that a common intrinsic normal-state property of high-$T_c$ superconductors is the occurrence of a field-induced MIT at low temperatures, and at a non-universal doping [2] of electron-doped Pr$_{2-x}$Ce$_x$CuO$_4$ is associated with a QCP at $p_c \approx 0.165$, at which remnants of the antiferromagnetic (AF) phase disappear. However, measurements of the MIC do not imply there is a competing magnetic order hidden in the SC phase at zero magnetic field. In fact, single-phase Pr$_{2-x}$Ce$_x$CuO$_4$ is difficult to grow, and magnetism is likely to reside in lightly doped regions of the sample at $H = 0$. Likewise, one could never draw a firm conclusion from earlier experiments on hole-doped La$_{2-x}$Sr$_x$CuO$_4$, showing that an external magnetic field enhances static magnetism in underdoped samples [11, 12, 16] and increases spin fluctuations in optimally or overdoped samples [17]. More recently, spin-density-wave (SDW) order was detected by neutron scattering at $H > 30$ kOe in a La$_{1.85-\delta}$Sr$_{0.144}$CuO$_4$ sample that did not exhibit static magnetic order at zero field [2]. Combined with earlier works, the neutron results support a proposed phase diagram [18] in which the pure superconductor undergoes a QPT to coexisting SC and SDW orders. However, neither the zero-field QCP deduced from the neutron studies, nor the QCP inferred from ZF-$\mu$SR experiments, correspond to the critical doping for the normal-state MIC. Kivelson et al. [19] have proposed that the ‘true’ field-induced QPT is one in which the competing order is stabilized in a halo around weakly interacting vortex lines. In this situation the magnitude of the competing order parameter is spatially inhomogeneous, and may only be detectable by a local probe technique.

For the present study we used weak magnetic fields applied perpendicular to the CuO$_2$ layers of La$_{2-x}$Sr$_x$CuO$_4$ and YBa$_2$Cu$_3$O$_y$ single crystals on either side of the critical dopings $x_c \approx 0.16$ [6, 7, 10] and $y_c \approx 6.55$ [1] for the MIC, to locally suppress superconductivity by formation of a vortex lattice (VL). The vortex cores were probed using $\mu$SR spectroscopy (at TRIUMF, Canada), which is an extremely sensitive probe of local internal magnetic fields. Like a tiny bar magnet, the magnetic moment of a muon implanted in a sample precesses about the local magnetic field $B$ with an angular frequency $\omega_\mu = \gamma_\mu B$, where $\gamma_\mu = 0.0852$ $\mu$s$^{-1}$ G$^{-1}$ is the muon gyromagnetic ratio. By measuring the time evolution of the muon spin polarization $P(t)$ via the anisotropic distribution of decay positrons, the internal magnetic field distribution $B(n)$ of the sample is determined [20]. ZF-$\mu$SR measurements at $T \geq 2.5$ K indicate that none of our samples contain static electronic moments, which is an essential requirement for establishing the presence of hidden competing magnetic order.

Figure 1 shows the ‘tail’ regions of the Fourier transforms of $P(t)$ measured in the vortex state of YBa$_2$Cu$_3$O$_y$ near the critical doping $y_c \approx 6.55$. The Fourier transform of $P(t)$, often called the ‘$\mu$SR line shape’, provides a fairly

*Electronic address: jsonier@sfu.ca
with static magnetism that is disordered. At tex cores [21], but in fact, this feature is also consistent
that the unusual high-field tail originates from AF vor-
previous
appearance of a low-field tail, the origin of which is ex-
creasing magnetic field, the observed changes in the tails
have been made equivalent by rescaling the horizontal
B
for the
y
accurate visual illustration of n(B) sensed by the nuons.
On the high-doping side of the MIC, the μSR line shapes
for the y=6.67, y=6.60 and y=6.57 samples are nearly
identical, while those for the y=6.50 and y=6.46 sam-
plies on the low-doping side of the MIC. Furthermore, the
moments. Here we find that this is not the case for sam-
static local-field inhomogeneity created by nuclear dipole
nuclear dipole 

In the vortex state, the μSR signal is described by

\[ P(t) = \sum_i \cos[\gamma \mu B(r_i)t], \]

where the sum is over all sites in the real-space unit
cell of the VL and B(r_i) is the local field at position
r_i = (x_i, y_i) with respect to the vortex center. Previous
studies [21] showed that the μSR signal from high-T_c
superconductors is well described by Eq. (1), assuming
a conventional phenomenological model for B(r_i) and
multiplying P(t) by a Gaussian function \( \exp(-\sigma^2t^2/2) \) to ac-
count for pinning-induced disorder of the VL [22] and the
static local-field inhomogeneity created by nuclear dipole
moments. Here we find that this is not the case for sam-
les on the low-doping side of the MIC. Furthermore, the
simple model introduced in Ref. [21], which assumed
perfect AF order in the vortex cores commensurate with the
crystal lattice, does not describe the low-field data pre-
sented here. Since static magnetic order is not detected
in La_{2-x}Sr_xCuO_4 near x=0.145 at H<30 kOe by neu-
tron scattering [3], the static magnetism detected here
must be disordered, such that the polarization function
is given by

\[ P(t) = \sum_i \exp(-\Lambda e^{-(r_i/\xi_{ab})^2}t) \cos[\gamma \mu B(r_i)t]. \]
FIG. 2: (Color online) Doping, temperature and magnetic field dependences of the \( \mu \)SR line shapes for La\(_{2-x}\)Sr\(_x\)CuO\(_4\). (a) Full \( \mu \)SR line shapes for samples above \( x = 0.176 \) and \( x = 0.166 \) and below \( x = 0.145 \) the critical doping \( x_c \approx 0.16 \) for the normal-state MIC. (b), (c), (d), (e), (f) Blowups of the ‘tail’ region of the \( \mu \)SR line shapes. The height and width of the line shapes have been normalized in the same way as in Fig. 1. Panels (b), (c) and (d) show the magnetic field dependence of the line shapes, and panels (c), (e) and (f) show the temperature dependence. (g) Temperature dependence of the relaxation rate \( \Lambda \) for La\(_{2-x}\)Sr\(_x\)CuO\(_4\) (circles) and YBa\(_2\)CuO\(_4\) (squares) at \( H = 5 \) kOe. The red and blue symbols denote samples on the high-doping and low-doping sides of the critical doping of the normal-state MIC, respectively.

For simplicity the relaxation rate here is assumed to fall off as a function of radial distance \( r \) from the vortex core center on the scale of the in-plane SC coherence length \( \xi_{ab} \), and the distribution of fields at each site is assumed to be Lorentzian, as is often the case in SG systems.

Figure 2(g) shows results of fits of the \( \mu \)SR signal for several samples to Eq. (2), assuming a simple analytical solution of the Ginzburg-Landau equations [23] for \( B(r_i) \). In the \( x = 0.145 \) and \( y = 6.50 \) samples at \( T = 2.5 \) K, the average magnetic field created by the magnetism at the site of a muon stopping in the center of a vortex core is approximately \( \pm 70 \) G, which is the half-width at half-maximum of the Lorentzian field distribution assumed in Eq. (2). This explains why the appearance of magnetism in and around the vortex cores also affects the low-field tail of the \( \mu \)SR line shape. The diverging temperature dependence of \( \Lambda \) indicates a slowing down of Cu spin fluctuations, entirely consistent with the approach to a second-order magnetic phase transition at \( T = 0 \) K.

We can rule out other possible origins of the observed changes in the \( \mu \)SR line shape across the MIC. First, a change in \( \xi_{ab} \) would alter the location of the high-field ‘cut off’, but would not change the amplitude of the high-field tail or introduce a low-field tail. Second, a change in symmetry of the VL affects the entire \( \mu \)SR line shape, not just the tails. In fact, if changes in \( \xi_{ab} \) and/or VL symmetry occurred, they would be detectable in our analysis of the \( \mu \)SR line shapes [24]. Third, we consider the possibility that an order-to-disorder transition of the VL occurs at the critical doping for the MIC. A field-induced Bragg-to-vortex glass transition has been observed by \( \mu \)SR and neutron scattering in severely underdoped La\(_{1.9}\)Sr\(_{0.1}\)CuO\(_4\) [25]. The static disorder in the vortex glass phase results in a highly symmetric and greatly broadened \( \mu \)SR line shape. However, here the \( \mu \)SR line shapes for the samples on the low-doping side of the MIC are narrower than those of the higher-doped samples, in accordance with an increase in the magnetic...
around weakly interacting vortices at the QPT. This confirms one of the main theoretical predictions of the modified phase diagram proposed by Kivelson and co-workers. The original theory of Ref. 19 assumed that the vortices are two-dimensional. By including the interlayer couplings of vortices in neighbouring CuO$_2$ layers, Kivelson et al. showed that a competing phase could be stabilized in nearly isolated vortices, thus altering the position and character of the QPT. In their extended theoretical model, the pure superconductor undergoes a field-induced QPT to a coexistence phase in which the competing order parameter (which we identify here as the mean squared local magnetization) is spatially inhomogeneous. With increasing field, stronger overlap of the magnetism around neighboring vortices may lead to a co-operative bulk crossover to long-range magnetic order, as is apparently the case in La$_{2−x}$Sr$_x$CuO$_4$.

A key prediction of the theory of Ref. 19 is that there is an ‘avoided’ QCP at $H = 0$ (Fig. 3). In other words, the QCP lies at a lower doping than one expects from the extrapolated $H → 0$ location of the QPT found here. Indeed, previous ZF-$\mu$SR measurements indicate that the onset temperature of static magnetism coexisting with superconductivity on a nanometer scale in La$_{2−x}$Sr$_x$CuO$_4$ [1,26] and YBa$_2$Cu$_3$O$_y$ [27,28], extrapolates to zero at a hole concentration below the critical doping for the MIC.

We thank S.A. Kivelson, R. Greene, B. Lake and E. Demler for informative discussions. J.E. Sonier, J.H. Brewer, R.F. Kiefl, D.A. Bonn, W.N. Hardy and R. Liang acknowledge support from the Canadian Institute for Advanced Research and the Natural Sciences and Engineering Research Council of Canada. Y. Ando acknowledges support from Grant-in-Aid for Science provided by the Japan Society for the Promotion of Science.

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