## Experiment E1100 & E1041 Nature of the Quantum Critical Transition in Electron-doped Superconducting Films of $Pr_{2-x}Ce_xCuO_4$ .

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One of the key questions about the phase diagram of high- $T_c$  cuprate superconductors vs. chargedoping is the occurrence and nature of *quantum critical points*, i.e. phase transitions at zero temperature, which are thought to control the electronic properties of the material over a wide range of temperature and doping, and may hold the key to the origin of the unconventional superconductivity. In E1100, we are studying the electron-doped family of cuprates  $(Pr_{2-x}Ce_xCuO_4)$ , which can be prepared as high quality thin films, but not readily as macroscopic crystals. For comparison, we have also studied the canonical hole-doped cuprate YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>. This also provides an important control measurement for E1041 which will be run when the deceleration capability is completed on the  $\beta$ NQR spectrometer. In our preliminary experiments on  $Pr_{2-x}Ce_xCuO_4$  and  $YBa_2Cu_3O_{7-\delta}$ , we measured the magnetic field distribution in the vortex state near optimal dopings.

## Optimally doped $Pr_{2-x}Ce_xCuO_4$

Our measurements were taken on a *c*-axis oriented  $Pr_{2-x}Ce_xCuO_4$  (PCCO) film (x = 0.15 and  $T_C \sim 20$ K) of 300nm thickness, epitaxially grown by pulsedlaser deposition on a SrTiO<sub>3</sub> substrate. We carried out the experiment on the high-field  $\beta$ NMR platform, where a beam of <sup>8</sup>Li<sup>+</sup> with kinetic energies ranging from E = 30 to 1 keV was implanted into a thin overlayer of Ag (40nm thick) evaporated onto the PCCO. By stopping in the Ag layer, we measure a field distribution due to the emergence of the magnetic field lines from the vortex lattice of the superconducting layer. The measurements were carried out in the vortex state by applying magnetic fields  $B > B_{c1}$ . Measurements of the temperature dependence of the  $\beta$ NMR resonance showed a dramatic broadening in the vortex state (below  $T_c$ ) as shown in Fig. 1-a. The FWHM versus temperature displayed in Fig. 1-b is temperature independent above the transition where the broadening is due to Ag nuclear dipolar fields. The broadening increases dramatically below  $T_c$ , indicating that a larger magnetic field inhomogeneity due to the formation of flux vortices However, the lineshape is symmetric or even has a negative skewness, which is inconsistent with the positive skewness expected for a regular triangular or square vortex lattice.



Fig. 1. (a) The  $\beta$ NMR resonance of the PCCO vortex state measured in a longitudinal applied field of 216 G. Inset: the profile of <sup>8</sup>Li<sup>+</sup> beam of 5keV energy stopping into Ag simulated using TRIM code. (b) The FWHM of Lorentzian fits of the resonance. (c) FWHM vs. *B* at temperatures 30K and 5 K. Inset: FWHM vs. *T* in an external field of 4.1T.

A disordered lattice may lead to a symmetric or negatively skewed field distribution [U. Divakar et al. Phys. Rev. Lett. 92, 237004 (2004)]. On the other hand, it is also possible that the vortex lattice is molten near the surface [A. De Col et al. Phys. Rev. Lett. 96, 177001 (2006)]. The extent of superconductivity in the phase diagram is relatively well-established. The symmetry of the superconducting ground state is more elusive, but also established in many systems. However, it has proven very difficult to follow the evolution of magnetism with doping. To determine whether  $Pr_{2-x}Ce_xCuO_4$  at this doping is magnetic, we measured the resonance in the normal state at T = 30 K and superconducting state at T = 5 K, at different applied fields. The FWHM of the field distributions as a function of applied field is plotted in Fig. 1-c. The additional field dependent broadening apparent above  $T_c$  indicates another nonsuperconducting source of magnetic inhomogeneity, such as might be expected from some form of magnetic freezing in the PCCO. The FWHM at 4.1 T plotted in the inset of Fig. 1-b against temperature clearly shows the existence of such magnetic broadening in the normal state.

Measurements of the field distribution for other dopings and other applied fields are planned in order to follow the evolution of magnetism and superconductivity, seeking evidence of a quantum phase transition. More samples of different dopings ranging from underdoped to overdoped will be studied next.

## Optimally doped $YBa_2Cu_3O_{7-\delta}$

Our measurements on PCCO proved to be unusual as the asymmetry of the field distribution does not show the known features of a regular vortex lattice. For completeness, we needed to confirm these results by performing control experiments on the well-studied YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7- $\delta$ </sub> (YBCO). For this purpose, we have measured the field distribution in a 120 nm Ag overlayer on an optimally doped YBCO crystal (~1mm thick,  $T_C$ =89 K). Such systems have been studied by Low-Energy  $\mu$ SR and revealed the emergence of a regular vortex lattice in the superconducting state [Phys. Rev. Lett. **83**, 3931 (1999)]. Here, we measured the resonance by stopping the <sup>8</sup>Li<sup>+</sup> in the Ag in an applied field 516 G. We find an asymmetric lineshape (see Fig. 2-a) with a noticeable positive skewness as expected. The FWHM in Fig. 2-b broadens with T smaller than  $T_C$  because of the inhomogeneity of internal fields in YBCO. The FWHM should decrease at higher applied fields as the vortices are packed more tightly (with spacing decreasing as  $1/\sqrt{B}$ ). However, the substantial broadening at high applied fields is inconsistent with this, suggesting that existing models for the field distribution in a normal metal overlayer need to be modified to include the superconductor/metal interface effects.



Fig. 2. (a) The  $\beta$ NMR resonance in Ag/YBCO measured in a magnetic field  $B_{\rm ex}$  of 516.7 G applied along YBCO *c*-axis. Inset: the profile of <sup>8</sup>Li<sup>+</sup> beam of 8keV energy stopping into Ag simulated using TRIM code. (b) The temperature dependence of the FWHM extracted from Lorentzian fits of  $\beta$ NMR data at 516 G and 33.3 kG.