High critical current density
superconductivity

FINAL REPORT
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This project was focused on a basic scientific problem, one that is at the heart of application and development of superconductivity for efficient energy usage. This is improvement in high current density which can only be achieved by learning to pin vortices to the physical structure of its underlying superconducting material. Quantized vortices are the tornado of electrical supercurrents, ubiquitously present in a type II superconductor similar to the water whirling out of a bathtub drain; the magnetic flux of these superconducting vortices is quantized. The promise of superconductivity for more efficient energy transport depends critically on developing a basic understanding of vortex pinning in the crystalline solid. Central to this agenda is the basic understanding of interactions between vortices, the quantum state of the vortex core, and the potential for pinning from materials defects. We address the former two items in our program.

Our approach is to study the vortex-vortex interactions and the stability of resulting vortex structures, as well as to investigate spectroscopically the vortex core electronic structure using small angle neutron scattering (SANS) and spatially resolved NMR methods. Our work has been on a class of superconductors called unconventional superconductors a class, which includes all high temperature superconductors and some heavy fermion superconductors. The former are where the potential applications will lie. The latter are a paradigm system where basic scientific questions can be addressed. We first completed a NMR study of vortex structures in the high-temperature, superconducting compound Bi$_2$Sr$_2$Ca$_1$Cu$_2$O$_{8.2}$ (Bi-2212) which we obtained in the form of very high quality single crystals from Professor S. Uchida’s group in Tokyo. We processed these crystals to exchange the more common isotope $^{16}$O with the rare isotope $^{17}$O which has a sensitive NMR signal. Our NMR spectrum and spin-lattice relaxation measurements support our model for a structural instability which we discovered in the vortex system at magnetic fields in the range of 4 to 6 T depending on chemical doping. We developed a model to explain this instability based on electrical charge of $\approx 10^{-3}$ e trapped on the vortex core. The results are now in press in Nature Physics to appear in November 2010.

The second part of this project was to perform SANS measurements of the vortex structures on the compound UPt$_3$. The SANS measurements were performed at PSI (Paul Sherrer Inst, Zurich) in collaboration with Professor Morten Eskildsen (University of Notre Dame and Argonne National Laboratory). The single crystal was 15 gm of world-class material grown at Northwestern University having a RRR of 800. Our first
results are displayed in Fig. 1 showing clearly the distorted six-fold pattern of the vortex structure associated with anisotropy in the penetration depth of this superconductor. In Fig. 2 we show the rocking curves from these measurements. In brief, these experiments demonstrate the feasibility of studying the vortex structure in this important paradigm system. The results shown here are significantly improved over earlier measurements performed by a group from Bell Laboratories. They offer the potential for new understanding using the SANS method. On the basis of our results with ISEN the collaboration between Eskildsen and Halperin was awarded a new 3 year DOE contract, “Metastable Vortex Lattices: Properties and Applications” $519,014.

**Technical Discussion:** For both the measured fields (0.4 and 0.6 T) the vortex lattice (VL) was prepared by a reduction of the applied field at low temperature (75 mK) from $H > H_{c2}$, followed by a small amplitude field oscillation. Fig. 1 shows a diffraction pattern obtained in the B-phase, revealing a distorted hexagonal VL in agreement with earlier reports [1,2]. The corresponding rocking curve is shown in Fig. 2 (red symbols). The rocking curve is well defined with a narrow width of 0.25°, somewhat larger than the experimental resolution (~0.15°). The blue symbols show the VL rocking curve at 0.6 T (C-phase) which have significantly reduced intensity, but at most a very modest broadening compared to the B-phase. This is in stark contrast to the results reported by Yaron et al. [2] and indicative of a significantly reduced vortex pinning in the Northwestern crystal. Furthermore, our results have a vastly improved signal-to-noise ratio compared to the earlier reports [1,2].

**Fig. 1** Diffraction pattern obtained with $H \parallel a$ at $H = 0.4$ T and 75 mK (B-phase). Only peaks close to the vertical axis were imaged (tilt-scan) and the distorted flux structure reflects the $ac$-anisotropy.

**Fig. 2** Rocking curve averages at 0.4 T (B-phase) and 0.6 T (C-phase) at 75 mK. The FWHM of the Lorentzian fits is $0.25^\circ\pm 0.01^\circ$ (0.4 T) and $0.30^\circ\pm 0.05^\circ$ (0.6 T).

**References:**