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# Magnetization of Stripe Phase Superconductors

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Magnetization measurements have been carried out for superconducting $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ in order to determine whether the the shape of the magnetization vs field (M vs H) curves for a stripe phase material are similar to classical superconductors and to other high temperature superconductors. Neutron scattering data have shown that this material is an antiphase domain antiferromagnet in which the holes collect in the domain walls of the antiphase domain structure. With this localization of holes, the superconducting order parameter might be space dependent and the vortex lattice might be different from ordinary Type II superconductors. A large region of thermodynamic reversibility is found, and the flux expulsion data show that this material is a good bulk superconductor with a free energy difference between the superconducting and normal state very similar to a classical superconductor like Nb. The shape of the magnetization curves (M vs H), however, has a double peak structure that is quite different from the predictions of classical Type II behavior and different from Y(123).

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## I. Introduction

Previous work by Tranquada and coworkers [1, 2] have shown that $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ has both a very unusual crystal structure and a complicated magnetic behavior at low temperature. As the sample is cooled below room temperature the orthorhombic crystal structure transforms to a low temperature tetragonal (LTT) structure at 70 K. In the room temperature orthorhombic structure, the oxygen octahedron tips along the (110) direction, but in the LTT structure, the oxygen octahedron alternately tips along the (100) and (010) directions in successive layers.

With further cooling to 60 K, the holes in every other $CuO_2$ layer will begin to line up in stripes along the a-axis with a. periodicity of about 4 unit cells. In the $CuO_2$ layers between these, the holes line up along the b-axis with the same 4 unit cell repeat distance. Hence, the direction of the hole stripes alternates by 90” every other layer. At yet a lower temperature, 50 K, the Cu moments line up in an antiphase domain antiferromagnet with approximately an 8 unit cell repeat distance. There are 3 rows of antiferromagnetic Cu spins with a domain wall and another 3 rows of antiferromagnetic Cu spins out of phase with the first 3 rows. The holes then lie along the domain walls of the antiphase domain antiferromagnet. The direction of the stripes changes from (100) to (010) in alternate layers.

All through this temperature range, the Nd ions are paramagnetic. With further cooling, the sample goes superconducting at 10.5 K. Finally, at about 3 K, the Nd ions order.

With this stripe-like structure to the distribution of charge carriers in the $CuO_2$ planes and a coherence distance in the a-b plane of about 2 nm, one might expect that the superconducting order parameter might have a space dependence in the a-b plane [3-5]. This is a genuine phase separation, and there might be at least two effects. First, the average free energy difference between the superconducting and normal state may differ from the law of corresponding states obeyed by classical superconductors that have a spatially uniform carrier density [3]. Second, the vortices may have a different shape and magnetization curves ($M$ vs $H$) may show a shape different from classical or other high $T_c$ materials [6]. Flux pinning may also be different, but that is not the subject of this paper.

The neutron scattering experiments initially were controversial. There had been phase diagram work [7] indicating that samples with a Sr content of 0.15 would not be superconducting even though there were magnetization studies in a few mT showing magnetic shielding. There were speculations that samples with phase separated holes would be superconducting as long as the antiferromagnetic fluctuations were dynamical, but as soon as the stripes were pinned as in this stripe phase sample, then the superconductivity would disappear. In this work, the first goal was to determine whether the same single crystal measured by the neutron scattering work was a good bulk superconductor by measuring the flux expulsion over a large region of the field-temperature, H-T, plane and thus determine the free energy difference between the superconducting and normal state [3]. In addition, it was hoped that the detailed shape of the reversible magnetization curves would reflect in some way, the spatially inhomogeneous superconducting order parameter. Hao-Clem theory [6] described the reversible $M$ vs $H$ curves of Y(123) and Y(124) [8] very well, so it is of interest to know how the $M$ vs $H$ curves of this $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ stripe phase material compare with Y(123) and Y(124).

## II. Results and discussion

The method used to subtract the normal state background of the Nd ions has been discussed previously [3]. The background is well described by Curie-Weiss approach with a Curie temperature close to 4 K and a Lande g-factor of 0.70, a value close to the free ion value. Fig. 1 summarizes the magnitization curves between $T_c$ and 5.0 K. At lower temperatures, the Curie-Weiss law does not describe the normal state very well and no results are presented for this region. As described previously, the area under these curves, $\int_0^{H_{c2}}$ MM, is the free energy difference between the superconducting and normal state and the thermodynamic critical field, $H_c$, can be defined by $G_N - G_S = \int_0^{H_{c2}} M dH = H_c^2/8\pi$. The irreversible portion of the curves is only a small fraction of the magnetic field range and this area is estimated by a linear extrapolation from the irreversibility field to $H = 0$. These thermodynamic critical fields have an uncertainty of about 20 to 30%, but to this accuracy, the critical field of $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ with $T_c = 10.5K$ is very similar to the thermodynamic critical field of Nb with $T_c$ = 9.25 [3].

The shape of the $M$ vs $H$ curves is rather different from either Hao-Clem [6] or Nb [9] or Y(123) [8] as shown in Fig. 2. As the magnetic field is lowered below $H_{c2}$ for Nb and Y(123), the magnitude of the magnetization rises monotonically to the value at $H_{c1}$. For

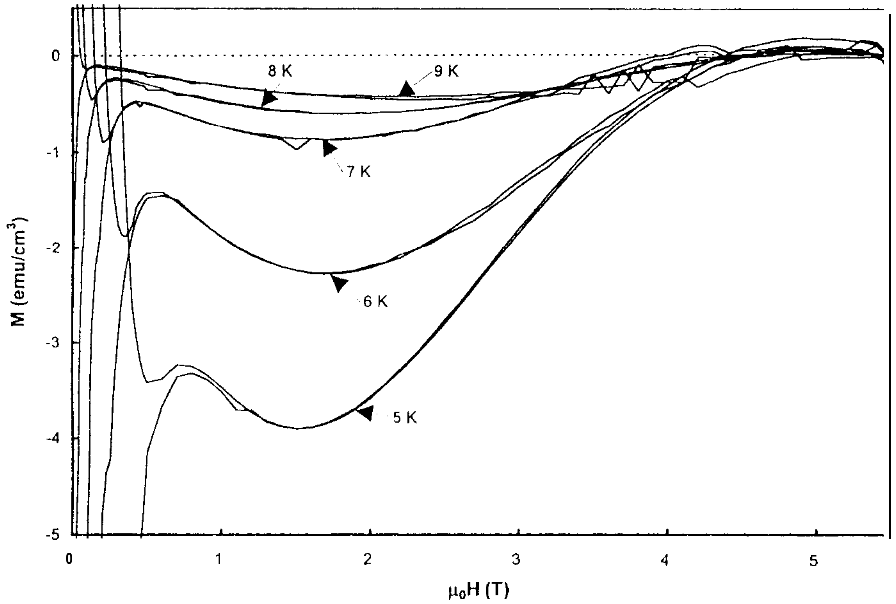

FIG. 1. Magnetization curves for the stripe phase superconductor, $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$

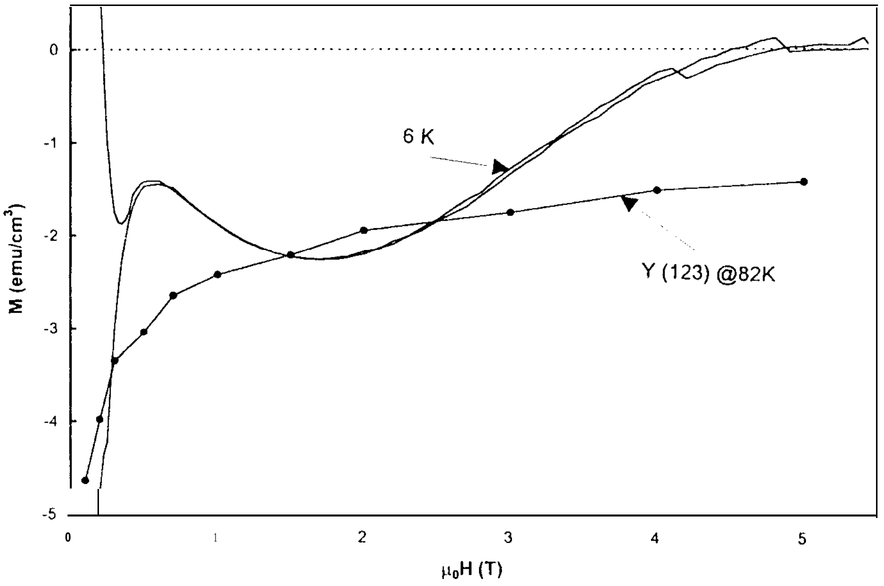

FIG. 2. Comparison of stripe phase magnetization with Y( 123).

$La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ as the magnetic field is lowered below $H_{c2}$, the flux exclusion rises to a peak at about 2 T and then fall to a valley at about 0.7 T with a subsequent rise at lower fields. These peaks and valleys have a small temperature dependence. The general shape of these magnetization curves is very robust and independent of the details of background subtraction.

In many ways, these non-monotonic reversible magnetization curves are similar to the non-monotonic reversible magnetization curves reported for Bi(2212) that has been irradiated with heavy ions to a matching field of 1 T [10]. A matching field of 1 T means that the average spacing of the ion channels is the same as the vortex spacing in a field of 1 T. These irradiated samples also have a space dependent order parameter caused by the 7 nm diameter amorphous channels parallel to the c-axis of the Bi(2212) crystal. As shown in the sketch of Fig. 3, magnetization of ion irradiated Bi(2212) shows more shallow peaks and valleys, but it has the same general shape. The explanation of the Bi(2212) result is that, at the matching field, most of the flux will reside in the amorphous damage tracks and cost little free energy. Off matching, the excitations in the vortex cores in the superconducting region of the sample will raise the free energy. For the stripe phase materials, the stripes are a factor of 10 closer together than the ion channels, so the two cases seem rather different when considered quantitatively.

## III. **Conclusions**

The shape of the superconducting magnetization curves for the stripe phase $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ is non-monotonic and quite different from Y(123) and Y(124). Both this stripe phase material and the ion irradiated Bi(2212) show similar non-monotonic behavior for the $M$ vs $H$ curves, but in detail they are different. As the field is lowered below $H_{c2}$,

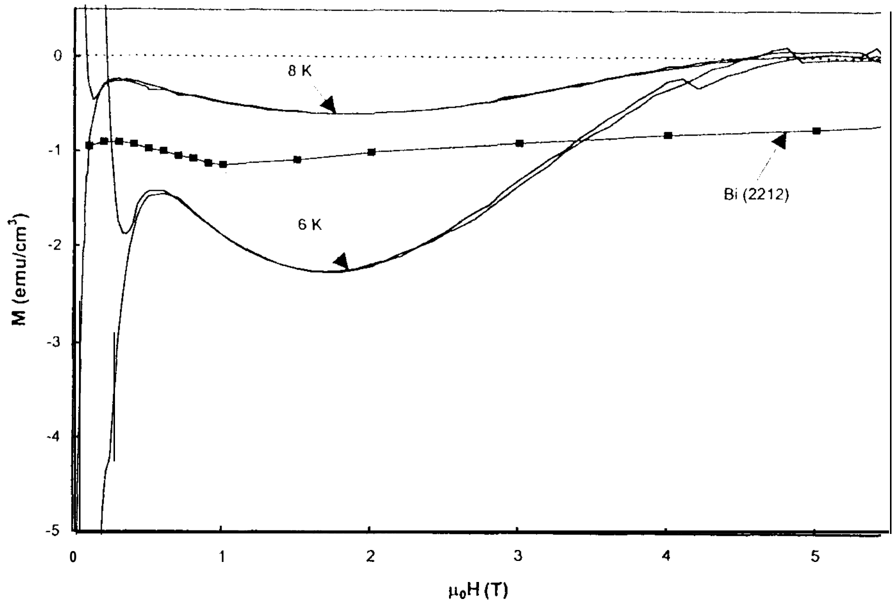

FIG. 3. Comparison of stripe phase magnetization with Bi(2212) irradiated with heavy ions to a matching field of 1 T.

say at 6 K, the magnitude of the magnetization rises to a peak at 1.8 T, goes through a minimum at 0.6 T, and then rises again at lower fields. The spacing of the stripes is much smaller than the spacing of the vortices at all of these fields, so a matching effect will not explain the stripe phase data.

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