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Vortex lattice structures in $\text{YBa}_2\text{Cu}_3\text{O}_7$

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ABSTRACT

We describe small-angle neutron scattering (SANS) studies of vortex structures in the high T_c superconductor $\text{YBa}_2\text{Cu}_3\text{O}_7$ in the mixed state. The SANS technique is a unique tool for probing the crystallography of a flux line arrangement in the bulk sample that can measure the values of the characteristic lengths and the effect of defects on lattice arrangement and orientation extremely accurately. The effects of crystal anisotropy on the field distribution in a vortex line is the topic of this paper.

In type-1 superconductors, an applied field is completely screened till the field strength exceeds the critical field. Any field larger than this causes the superconductor to become normal, that is, non-superconducting. In 1957, Abrikosov¹ in his theory of type-II superconductors predicted the existence of the 'mixed' state, where flux carried by quantized flux lines or vortices penetrate the bulk material, causing parts of the superconducting material to become normal. This occurs for applied fields (B) such that $H_{c1} < B < H_{c2}$, where H_{c1} and H_{c2} are the lower and upper critical fields respectively. The flux lattice is also referred to as an Abrikosov lattice.

The interaction between vortices is repulsive, hence vortices form a lattice which maintains the maximum distance between them. Each vortex line contains a total flux equal to the flux quantum $\Phi_0 = hc/2e$, where h is Planck's constant, c is the speed of light and e the charge of an electron. Hence the total number of flux lines in the sample is determined by the external applied field. The inter-vortex spacing for a triangular isotropic lattice is given by:

$$d = \left(\frac{\sqrt{3}}{2} \frac{\Phi_0}{B} \right)^{\frac{1}{2}} \quad (1)$$

For an applied field of 2000 Gauss, this distance is approximately $950 \text{ \AA}$, corresponding to a q -value of $0.0066 \text{ \AA}^{-1}$. The vortex is a line of magnetic flux; the lateral extent of the field distribution is determined by the London penetration depth, λ_L .

The arrangement of flux lines were first observed in Bitter patterns or decoration experiments. When a thin layer of finely ground ferromagnetic particles are deposited on the surface of a superconductor and then cooled in a field, the magnetic dust settles at the normal cores. The resulting decoration reflects the underlying field distribution. Extremely clear decorations have been seen by a number of groups, both in the conventional as well as in the high T_c materials. It is also the method by which defects in vortex lattices were first observed. More recently, scanning tunneling microscopes equipped with a magnetic tip have been used to look at the field distribution in conventional superconductors. The most serious limitation of both these quite techniques is that they probe only the surface. Also, the fields used to get a good decoration must be quite low to distinguish between the cores. To their advantage, samples can be quite small. Invariably, more perfect samples can be obtained when large size is not a restriction.

Small-angle neutron scattering experiments were first suggested by deGennes and Matricon². (Since neutrons have a magnetic moment, they interact with the field modulation caused by an array of flux lines.) Shortly thereafter, a Bragg diffraction peak from a flux line lattice corresponding to the predicted triangular arrangement was observed by Cribier and co-workers³ in a single crystal sample of niobium on which a magnetic field was applied. Since then, extensive measurements have been made in Jülich⁴ and Oak Ridge,⁵ on niobium as well as other superconductors, probing the details of the lattice structure, the effect of defects, the exact nature of the form factor and of the temperature-dependent order parameter. The intensity of a diffraction peak is given by:

$$\frac{I}{I_0} \propto \frac{1}{q} \left(\frac{B}{\phi_0} \right)^2 \left(\frac{1}{1 + q^2 \lambda_L^2} \right)^2 \quad (2)$$

where I_0 is in the incident neutron flux, λ_L is the London penetration depth, B is the magnetic field and ϕ_0 is the flux quantum.

The London depth is approximately the full-width at half-maximum of the field distribution of a single flux line, hence there is less contrast for larger λ_L . For niobium, $\lambda_L \approx 400 \text{ \AA}$, whereas for the high T_c materials, it is at least 3 times larger. Hence, the signal to be measured is lower by approximately two orders of magnitude. Also, the signal for the first order reflections, barring other complications, is relatively independent of the applied field except for a geometrical $1/q$ factor. On the one hand, there is less contrast between the peak and valley at a higher field due to larger number of flux lines; on the other, the number of scatterers is higher which balances the equation. However, there is considerable gain in utilizing a larger field in order to get away from the incident beam and the metallurgical scattering as much as possible in order to increase the signal to noise ratio.

The high T_c superconductors are highly anisotropic. In general, these compounds are nominally uniaxial systems since the a - b (basal plane) anisotropy is fairly small and the c -axis is considerably different. In $\text{YBa}_2\text{Cu}_3\text{O}_7$, the crystal structure is nearly tetragonal with $c \approx 3a$ and the a/b ratio is approximately 0.99. Consequently, the high symmetry configuration for the observation of the vortex lattice is with the applied field parallel to the crystallographic c -axis of the crystal.

All the data shown in this paper were taken on 30-m SANS instrument at the High Flux Isotope Reactor (HFIR) in Oak Ridge. The sample was an 7.8g single crystal of oxygenated $\text{YBa}_2\text{Cu}_3\text{O}_7$ which has a superconducting transition at 92.4K with a transition width of $\sim 1\text{K}$. This indicates a fully oxygenated specimen. However, the sample contains 15% of a second phase. The first observation⁶ of the vortex lattice in $\text{YBa}_2\text{Cu}_3\text{O}_7$ was in data taken at the ILL in the above-mentioned high symmetry geometry with $B//c$. Since then, the signal has been observed at Oak Ridge much more clearly⁷ in the larger single crystal. In both measurements, the field, the incident neutrons and the c-axis were aligned such that they were collinear. A typical SANS area detector can then measure all scattering angles at once. Figure 1 shows a contour plot of the scattering pattern with square symmetry with Bragg peaks aligned along the (110) directions of the crystal that was observed. The flux line signal is seen in a difference between scattering between a temperature of 10K and high temperature (100K), effectively subtracting the metallurgical background. The square symmetry was contrary to the expected hexagonal lattice. Scattering with square symmetry has been observed in niobium along particular crystallographic directions and are thought to reflect nesting features in the Fermi surface.

In this case, however, it is most likely that the four peaks are due to flux line pinning by the two sets of twin plane defects, which are orthogonal to each other. In general, large samples of $\text{YBa}_2\text{Cu}_3\text{O}_7$, are twinned. Here the a and b axis interchange at a twin defect. The reason that defects pin flux lines is because these regions are less superconducting than the bulk, or sometimes, not superconducting at all. It is energetically favorable for the flux line to through as much normal material as possible; this way the energy loss that it incurs on becoming normal at a flux core is minimized. Planar defects are particularly effective since they can pin the flux line along their its length when aligned parallel to it.

Figure 1: Signal from scattering due to flux lines is seen in the difference data between 10K and at 100K with an applied field of 8kOe.

The square symmetry observed in Fig 1 is due to two domains, one from each of the 2 (110) directions. A careful analysis of the azimuthal peak width revealed that the intrinsic $\delta d/d$ of the scattering is $35 \pm 10\%$, which is extremely large. The word "lattice" is

hence used very loosely in the case of the $B//c$ data. However, in spite of this rather short range positional order, the orientational order of the lattice is quite good. Over the macroscopic dimensions of the entire crystal, each of the two domains are aligned exactly along the corresponding twin plane directions. The spot width in the tangential direction is limited by the resolution of the instrument.

We found that the London penetration depth in the basal plane, which is measured with $B//c$, was approximately $1600 \text{ \AA}$. This is an upper limit on the value since it would not be possible for us to have measured more neutrons than were scattered. Disorder, which is implied by the 35% $\delta d/d$, would decrease the observable intensity. Hence, it is no surprise that the London penetration depth obtained from our data is somewhat larger than $1400 \text{ \AA}$, which seems to be most common value, although there is some scatter in the numbers. It is likely that some of this scatter is sample-dependent.

There has been animated discussion about what role the anisotropy, which exists in the high T_c materials, plays in superconductivity mechanism. In an anisotropic material, the London penetration depths along the two directions are quite different from each other. This results in the field distribution of an individual flux line having an elliptical rather than circular cross-section. Hence, the stacking cannot be in an equilateral triangle, but rather in a distorted triangle.

With the field along the neutron beam direction, the sample was rotated about the (100) crystal axis by an angle Θ . This rotation axis is strictly speaking a mixture of (100) and (010) axes since our sample is twinned. The difference data for $\Theta = 60^\circ$ is shown in Fig. 2.

Figure 2: Flux line lattice seen in difference data for the case when the 8kOe applied field is 60° from the crystallographic c -axis.

Twelve diffraction peaks are observed, which are due to two six-fold lattices that are related to each other by symmetry. The structure predicted for this lattice⁸ is not the one observed. The real and reciprocal space lattices for one of the domains is shown in Fig.3 for $\Theta=60^\circ$. The second domain is related to the first by a simple ($X \rightarrow -X$) transformation.

Figure 3: a) The real space arrangement of flux lines and b) the corresponding reciprocal lattice for the case where the applied field is 60° from the c -axis.

From these data, the mass anisotropy ratio can be determined. This is the ratio of the effective mass of the electron in the basal plane and perpendicular to the basal plane. The mass anisotropy ratio determines the axial ratio of the ellipse on which all scattering falls, irrespective of the flux lattice structure. From data taken at $\Theta = 30^\circ, 45^\circ, 60^\circ, 70^\circ$, and 80° , the mass ratio is 20 ± 2 .

Figure 4: Temperature dependence of the Bragg intensity for $B // c$, $B 45^\circ$ from c , and $B 60^\circ$ from c are plotted. The solid line is a conventional (2-fluid) relation.

Perhaps the most unusual feature of the FLL in $\text{YBa}_2\text{Cu}_3\text{O}_7$ is the temperature (T) dependence of the Bragg intensity. Most conventional theories predict very little

variation in the intensity between 0 K and $\sim T_c/3$. Here, we see the intensity drop at the lowest temperatures measured as shown in Fig. 4. Since the T-dependence is different for B//c and B 60° from c, it is clear that the twin planes alter the T-dependence when B//c. Since the London penetration depth (of which the Bragg intensity is a measure) is an order parameter of the superconductivity, the unexpected T-dependence at low T is extremely interesting, particularly the implication on the mechanism driving the transition in these materials.

Much more remains to be done on flux lattices in these materials using small-angle neutron scattering techniques. Measurements of possible melting of the flux lattice near the critical temperature are planned. Untwinned samples of this compound will be a tremendous help in distinguishing between intrinsic properties of YBCO and those features that are twin-plane dependent. Clearly, SANS has been well established as a technique to measure vortex lattices in superconductors.

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