Physica C 235-240 (1994) 2705-2706
North-Holland

PHYSICA C

EVIDENCE OF THE COEXISTENCE OF TWO VORTEX ORIENTATIONS IN TILTED MAGNETIC FIELDS IN $Bi_2Sr_2CaCu_2O_{8+\delta}$

I.V.Grigorieva[a], J.W.Steeds[a], G.Balakrishnan[b], D.M.Paul[b].

[a] Physics Depertment, University of Bristol, Bristol BS8 1TL, UK
[b] Physics Department, University of Warwick, Coventry CV4 7AL, UK

We present a detailed study by the Bitter decoration technique of the mixed vortex chains-FLL phase found in tilted magnetic fields in BSCCO. We show that this new vortex phase can be understood if one assumes that the chain and FLL vortices have two different orientations, both not parallel to the applied field.

A novel vortex structure observed in tilted magnetic fields in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) [1] remains unexplained so far. This structure consists of vortex chains and an intervening vortex lattice (FLL). From the point of its evolution with external field and tilt angle, it is different from both the "pure" vortex chain phase in YBCO [2] and a vortex chain-FLL mixture in Al-doped YBCO [3]. In the latter two, formation of the vortex chains is attributed to the anisotropy-induced intervortex attraction. Recent theoretical calculations [4] have shown that in superconductors with extremely high anisotropy, like BSCCO or TBCCO, the tilted vortex lattice orientated parallel to the applied field, $\mathbf{B}_{ext}$, may become unstable, and may be replaced by a "combined" vortex lattice consisting of two types of vortices both of which are not parallel to $\mathbf{B}_{ext}$.

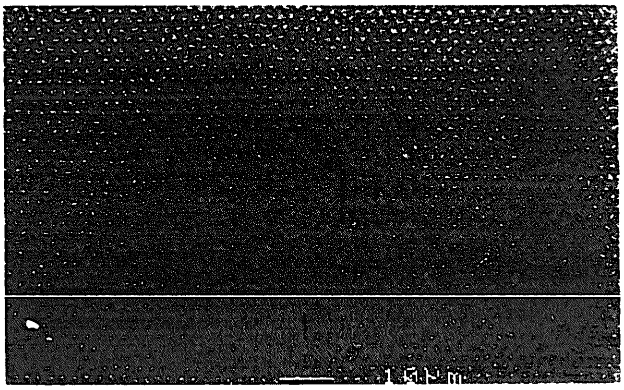

Figure 1.

Here, we present a detailed study of the vortex chain state in BSCCO by the Bitter decoration technique. Decorations were performed at 4.2K, after field-cooling, on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with typical dimensions 2x2x0.01-0.05mm^3. For every tilt angle, several crystals were studied, most of them from the same batch. For tilt angles $55<\varphi \leq 87°$, the usual isotropic FLL was replaced by a mixture of the vortex chains and the intervening FLL, as shown in Fig.1 ($\varphi=70°$, B_{ext}=20G; (**B**,**c**) plane is horizontal). Similar to ref.[1], we find that for a given φ, the intrachain vortex spacings, a_{ch}, the FLL vortex spacings, a_{FLL} and the distances between the chains all change

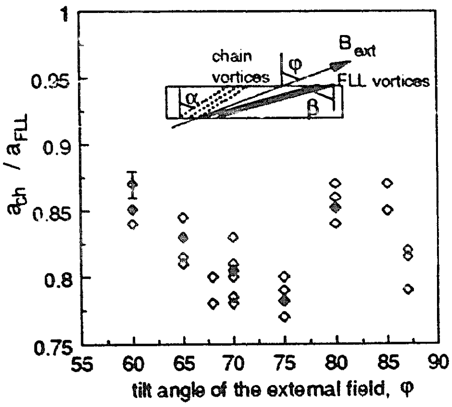

Figure 2.

with field as $\propto 1/\sqrt{B}$, where $B=B_{ext}\cos\varphi$. In the present experiment, we paid particular attention to the tilt angle dependencies of the vortex spacings because they should be an indication of anisotropy-induced properties of vortices in this material. We find that the intra-chain vortex period, a_{ch}, is practically independent of φ. However, the FLL period, a_{FLL}, goes through a maximum at φ=70-75° and, as a result, their ratio, a_{ch}/a_{FLL}, shows a minimum at these angles, as in Fig.2. (A downturn for $\varphi>80°$ is related to a thin-slab-shape of the crystals, as will be discussed below). The number of vortex rows between the chains, D_{ch}/a_{FLL}, decreases with φ rapidly and monotonically (Fig.3) that indicates an increase of the fraction which the chain

0921-4534/94/$07.00
SSDI 0921-4534(94)01918-5

vortices make in the mixture. From the absence of a tilt angle dependence for a_{ch} and its $\propto 1/\sqrt{B}$ dependence on field we conclude that there is *no* attractive well in the intervortex interaction potential in BSCCO [2,3]. We will now show that, instead, the observed vortex behaviour can be understood if one assumes that the difference between the chain and the FLL vortices lies in their different orientations (see inset in Fig.2). It is well known that the average vortex

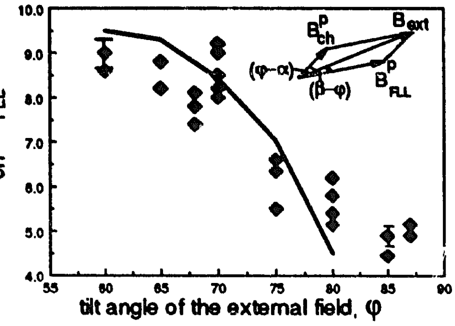

Figure 3.

density at the surface of a tilted crystal is defined by the normal component of the field, $B=B_{ext}\cos\varphi$. If the tilt of the chain vortices, α, is $\alpha<\varphi$ and the tilt of the FLL vortices, β, is $\beta>\varphi$, we obtain $a_{ch}\propto 1/\sqrt{(B_{ext}\cos\alpha)} < a$ and $a_{FLL}\propto 1/\sqrt{(B_{ext}\cos\beta)} > a$. One of the likely arrangements of such two vortex species is a larminar structure, like the one we observe, which accomodates the direction of tilt and the anisotropy axis, c. We calculated the angles, α and β, from the observed a_{ch} and a_{FLL} as follows:

$$\alpha[\beta] = \arccos\left[\left(\frac{2}{\sqrt{3}}\frac{\Phi_0}{a_{ch}^2\,[a_{FLL}^2]}\right)\Big/ B_{ext}\right];$$

the results are shown in Fig.4. The solid line shows orentations of the external field; the inset shows an angular split between the two types of vortices. One can see that for φ<80°, the orientation of the applied field lies in between those for the chain and the FLL vortices. However, for all the crystals decorated at φ= 85 and 87° and for some decorated at φ=80° we find that *both* the chain and the FLL vortices are tilted *less* than the applied field; accordingly, the average magnetic induction observed at the surface of these samples is higher than $B_{ext}\cos\varphi$. This finding is very surprising because, according to the relevant theoretical calculations, for fields nearly parallel to the CuO planes, one would expect a lock-in transition for the vortices or at least their orientation to become closer to the CuO planes, not to tilt further away from them. We attribute the decreased slopes of the vortices to the effect of crystal shape. It was shown recently [5] that in thin

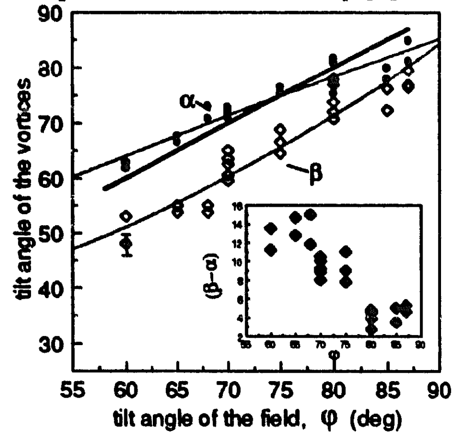

Figure 4.

slabs of an anisotropic superconductor in *low* fields, the slope of vortices should fall below the slope of the external field. Following [5], we found that this effect is particularly strong for the highest tilt angles. The details will be published elsewhere.

We find further arguments to support our scenario in calculations of partial fields induced by the chain and FLL vortices and of the D_{ch}/a_{FLL} ratio. Firstly, in the case of angular split of the vortices, the applied field, B_{ext}, should be equal a sum of the partial fields induced by the chain vortices, B_{ch}^P, and the FLL vortices, B_{FLL}^P. We find that this relation is satisfied to a high accuracy for all our samples. Secondly, we *calculated* D_{ch}/a_{FLL} ratio which one should expect if the chain and the FLL vortices *do* have different orientations. From simple geometrical considerations we obtain:

$$\frac{D_{ch}}{a_{FLL}} = \frac{\sqrt{3}}{2}\left(\frac{\cos\beta}{\cos\alpha}\right)^{1/2}\cdot\frac{\sin(\pi+\alpha-\beta)}{\sin(\beta-\varphi)}$$

The results are shown by the solid curve in Fig.3 (the initial data on a_{ch} and a_{FLL} used to find α and β are shown by filled symbols in Fig.2). One can see that the calculated values of D_{ch}/a_{FLL} reproduce rather well its rapid and monotonic decrease which we observe in experiment.

[1] C.A.Bolle et al, Phys.Rev.Lett. 66 (1991) 112
[2] P.L.Gammel et al, Phys.Rev.Lett.68 (1992)3343
[3] I.V.Grigorieva et al, Phys.Rev.B 48(1993)16865
[4] A Sudbø et al, Phys.Rev.Lett. 71 (1993) 1451; E.Sardella, M.A.Moore, Phys.Rev.B 48 (1993)9664
[5] E.H.Brandt, Phys.Rev.B 48 (1993) 6699