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Vortex overlapping in high temperature superconductors

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We have argued that the overlapping of vortices in the mixed state of high temperature superconductors (HTSCs) is important in the intermediate field range because of large Ginzburg-Landau parameter κ. Because of the anisotropic behavior, this effect is more pronounced for the applied field B_a parallel to c−axis than that for B_a parallel to ab−plane. In case of conventional superconductors, though the overlapping occurs near the upper critical field (B_{c2}), the overlapping is stronger compared to HTSCs.

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The small value of coherence length ξ and large value of penetration depth λ of the high temperature superconductors (HTSCs) differentiates itself from conventional type-II superconductors. Thus, the value of Ginzburg-Landau (GL) parameter κ and the upper critical field (B_{c2}) is extremely high compared to conventional type-II superconductors.

In the mixed state the separation d between the two lines is given by $d = \sqrt{\phi_0/B}$, where ϕ_0 is the flux quantum and B is the magnetic flux density. The magnetic flux density B increases on increasing the applied magnetic field and hence, the interspacing between vortices decreases. For low applied fields, the separation between the lines is much larger than the penetration depth and the lines are essentially independent. When d becomes comparable with λ, the electromagnetic regions of adjacent flux lines start to overlap.

According to the London theory, the distribution of local field is given by [1],

$$h(r) = \frac{\phi_0}{2\pi\lambda^2} K_0(\frac{r}{\lambda}). \tag{1}$$

i.e it decays like

$$h(r) = \frac{\phi_0}{2\pi\lambda^2} ln\frac{\lambda}{r} \quad for\ \xi < r < \lambda \ and \ = \frac{\phi_0}{2\pi\lambda^2}(\frac{\lambda}{r})^{1/2}e^{-r/\lambda} \quad for\ r >> \lambda \tag{2}$$

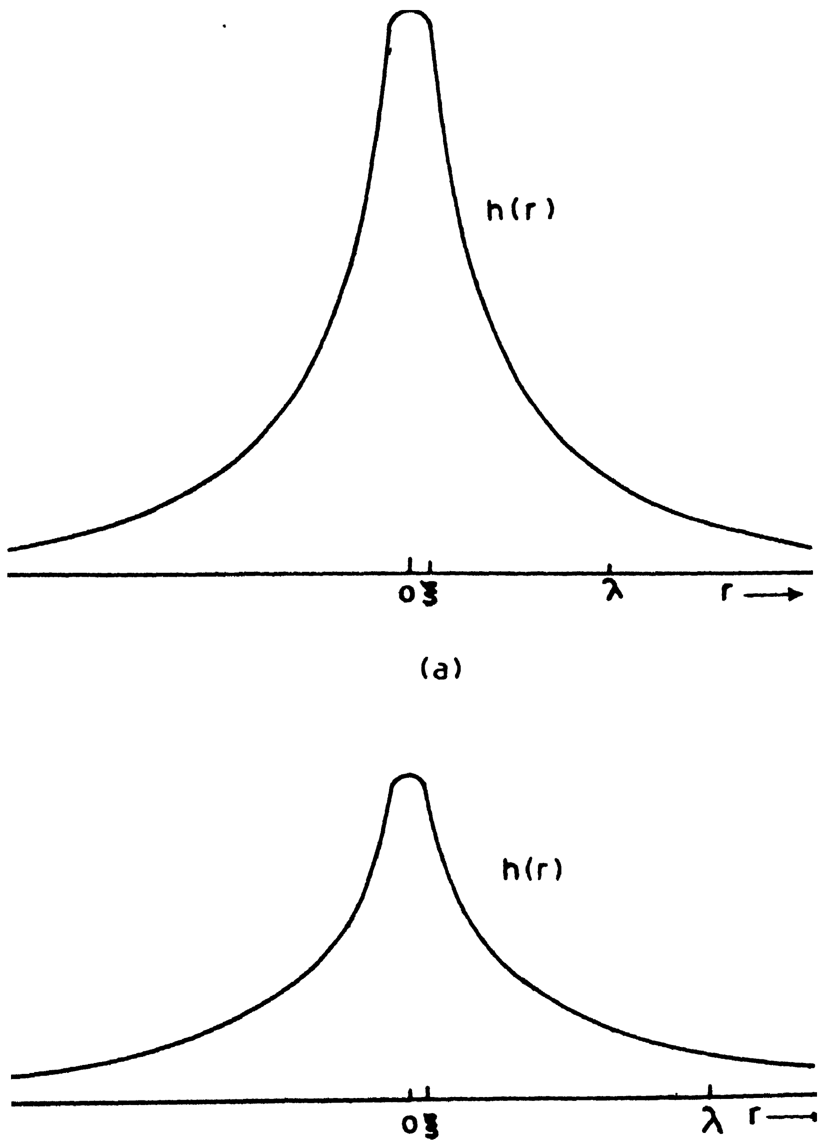

Fig. 1

Structure of an isolated vortex line in a material with (a) κ=10 and (b) κ=20.

This implies that $h(r)$ diverges logarithmically as $ln\ \frac{\lambda}{r}$ as $r \rightarrow 0$. In reality this divergence is cut off at $r \sim \xi$, where $|\ \psi^2\ |$ starts dropping to zero. Thus, $h(r)$ is regular at the center of the vortex line and is maximum which is given by,

$$h(0) \approx \frac{\phi_0}{2\pi\lambda^2} K_0(\frac{\xi}{\lambda}) = 2B_{c1}. \tag{3}$$

For the samples whose λ is large, the field value at the center of vortex line is less and the decay of field $h(r)$ with distance is slow. For conventional type-II superconductors, the κ value is small compared to HTSCs and the decay of magnetic field $h(r)$ is faster in the former case as is evident from Fig 1. The field value $h(r)$ goes to zero at a short distance from the center of the vortex lines. Thus, in case of conventional type-II superconductors, the value of λ is such that it is comparable to the interspacing between vortices near the upper critical field B_{c2} and thus, the vortex overlaps near B_{c2}. Whereas, the value of λ of any HTSCs is so large that it is comparable to d even at low applied fields. Thus, the vortices overlap for low field values and the vortex overlapping mechanism can be applied to understand the mixed state.

A single isolated vortex line consists of a normal core of radius ξ where the magnetic field strength at the center is $h(0) = (\phi_o/2\pi\lambda^2)K_o(\xi/\lambda)$ and decays as $K_o(r/\lambda)$ with distance and at a distance of λ it becomes $h(\lambda) = (\phi_o/2\pi\lambda^2)K_o(1)$ *i.e* reduces by a factor $\frac{K_0(\xi/\lambda)}{K_0(1)}$ [1]. If the applied field is such that flux-line lattice (FLL) with d comparable to λ, the vortices start overlapping, the superposition of magnetic field contributions of individual flux line increases the magnetic field strength, even at the centre of the vortices. The decay of the field becomes slower and the ratio $h(0)/h(\lambda)$ will be obtained at a distance greater than λ. We will have an effective penetration depth λ_{eff} larger than λ. If the applied magnetic field is increased further, the field strength B increases and the interspacing between vortices $d = (\phi_o/B)^{1/2}$ decreases, overlapping of electromagnetic regions of vortices becomes stronger, thereby increasing the value of λ further *i.e.* the penetration depth is field-depdendent and is given by,

$$\lambda_{eff} = \lambda/(\bar{f}^2(B))^{1/2}, \tag{4}$$

where $\bar{f}^2(B)$ is the spatial average of f^2, f being the magnitude of the order parameter, normalised to its value in the zero magnetic field and is given by $f^2 = 1 - X$, where $X = B/B_{c2}$ [2]. It can be noted from Eq. (4) that as the upper critical field is small in case of conventional superconductors compared to HTSCs, the overlapping in former case is stronger than the later at a particular field *i. e.* when the interline separation is comparable to λ, the vortices will start overlapping and will be stronger compared to HTSCs.

It has been found from magnetization measurement on a grain-aligned Y(123) crystal that the magnetization behaves as $(T-T_c)^2$ near the transition temperature T_c [3,4] and the change in specific heat by the application of magnetic fields ΔC is not linear in B_a [3] which can be understood by the vortex overlapping mechanism [5]. As the HTSCs are anisotropic, the magnetic field dependence of specific heat depends on the orientation of B_a with respect to the crystallographic axes. For any general orientation of B_a, the magnetization is [5],

$$M = \frac{\phi_0 f^2 \gamma^{-1/3} \epsilon(\theta)}{32\pi^2 \lambda_m^2} ln(\frac{\gamma B_{c2}^{||C}}{\epsilon(\theta) B_a}). \tag{5}$$

and the change in specific heat is,

$$\Delta C = \frac{\phi_0 B_a f^2 \gamma^{-1/3} \epsilon(\theta)}{16\pi^2 T_c \lambda_m^2(0)} \frac{t}{1-t} \tag{6}$$

with $f^2 = (1 - \frac{B_a \epsilon(\theta)}{\gamma B_{c2}^{||c}})$ and $\lambda_m = (\lambda_{ab}^2 \lambda_c)^{1/3}$, where $\epsilon(\theta) = (sin^2\theta + \gamma^2 cos^2\theta)^{1/2}$, θ is the angle between B_a and crystallographic $c-$axis, γ is the anisotropy of the effective mass, $B_{c2}^{||c}$ is the upper critical field for B_a parallel to $c-$axis and λ_{ab} and λ_c are the penetration depth parallel and perpendicular to $ab-$plane respectively. Here, we have considered the GL temperature depnedence of ξ and λ [1]. Though the magnetization is approximately logarithmic in B_a, the results obtained from this mechanism at low fields are in between that obtained from the usual London theory and the variational approach proposed by Hao *et al.* Expanding the logaritmic term near B_{c2} we see that the magnetization behaves as $(T-T_c)^2$ that has been observed experimentally [3,4].

We analyse the specific heat data of Athreya *et al.* [3] and obtain the $B_{c2}^{||c}$, $\lambda_{ab}(0)$ and γ as follows. In the mean field region ν=1/2. The least square fitted value of $B_{c2}(0)$ and $\lambda_{ab}(0)$ are found to be 296 T and 1936 Å from the specific heat data for $B_a \parallel c-$axis. We take T_c=93 K. The value of $\lambda_{ab}(0)$ is comparable with $\lambda_{ab}(0)$=1400±500Å obtained from magnetization measurement [6] and the value of B_{c2} is also in excellent aggreement with that obtained from magnetization measurement [7]. Using this $\lambda_{ab}(0)$, $B_{c2}(0)$ and the data for $B_a \perp c-$axis, the least squares fitted value of γ is estimated to be 6.1 which is in reasonable agreement with earlier reported value [8]. The least square procedure obtains the λ_{ab}=2334 Å and γ=4.3 where we have used the usual London theory result [9]. Fig. 2 shows the comparison of the data of Athreya *et al* [3] and the least-square

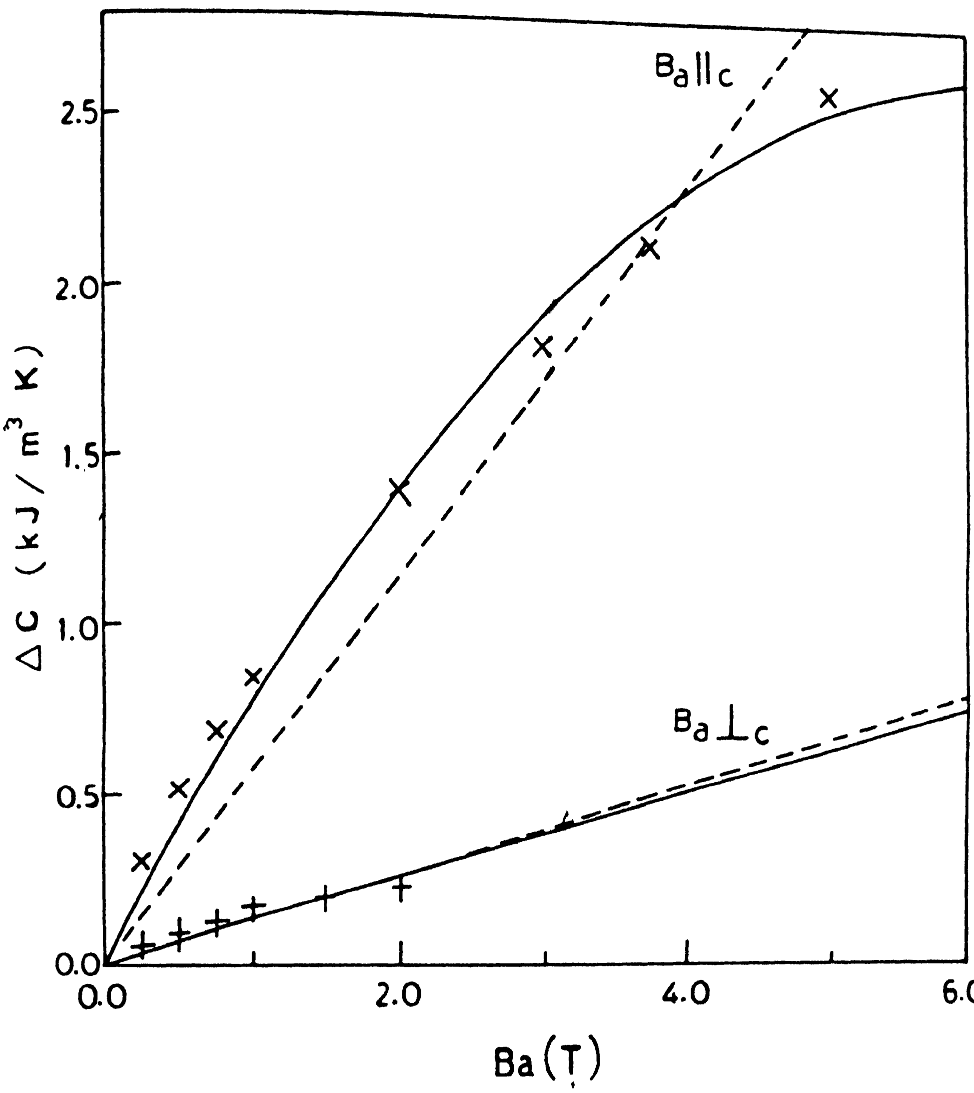

Fig. 2

The field dependence of ΔC of a grain-aligned Y(123) crystal. The data is obtained from Fig 5 of Ref 3. The solid lines are the theoretical curves according to Eq (2) and the dashed lines are the usual London results [9].

fitted theoretical curves for a grain-aligned Y(123) crystal. The solid lines are the theoretical curves according to Eq. (2) and the dashed lines are the usual London results [9]. It is noted that the vortex overlapping mechanism gives better fit to the experimental data and the overlapping is weak when the applied field is parallel to $ab-$plane. In this direction, the field would penetrate in the form of Josephson vortices with mutual distance $d = \phi_0/Bs$ [10], where s is the interlayer spacing. These form a FLL consisting of isosceles triangles [11]. If the applied field is parallel to $a-$axis, $h(r)$ decays with distance along $b-$axis with decay length λ_c and decays with decay length λ_{ab} along $c-$axis [12], *i. e.* the field $h(r)$ decays faster along $c-$axis and slowly along $b-$axis as $\lambda_c > \lambda_{ab}$. Also, the field strength at the center of the vortex line is low compared to that when the field is applied along $c-$axis. In the intermediate field range the distance between vortices $d = \phi_0/Bs$ is so large that the overlapping of vortices is weak.

In conclusion, we have given an argument that the overalapping of vortices in the mixed state of HTSCs is because of large κ. Thus, the vortex overlapping mechanism could be used to understand the thermodynamic properties of the HTSCs in the mixed state.

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