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# Vortex phases in irradiated highly anisotropic layered superconductors

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Resistivity, reversible magnetization, and Josephson plasma resonance (JPR) data for $Bi_2Sr_2CaCu_2O_8$ with columnar defects (CD) show that two liquid phases exist above the irreversibility line. They differ by the $c$-axis correlations in pancake positions. We explain the existence of two liquids with different $c$-axis correlations and transition between them in some temperature interval exploring the particle-hole symmetry in the free energy functional for pancakes inside CD. This functional accounts for magnetic interaction of pancakes, their interaction via Josephson coupling, and pinning by CD. [S0163-1829(98)50710-2]

The properties of the vortex state in highly anisotropic superconductors are a subject of intensive current interest. One of the central questions is the mechanism of the melting transition and the nature of the resulting liquid phase. Recent progress in both experimental and theoretical studies brought several evidences that vortex lattice melting in highly anisotropic $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) crystals is characterized by the loss of not only the *transverse* long-range order but by the disappearance also of the $c$-axis correlations.[1–4] Accordingly, the constitutive elements of the liquid state are distinct pancake vortices rather than pronounced vortex lines. Scaling of resistivity and magnetization with the $c$-axis component of magnetic field which determines the concentration of pancake vortices[5] and existence of the crossing point[6] lends further support for the ''pancake liquid concept.''

The columnar defects produced by the bombardment of superconducting crystals with heavy ions seem to promote pancake alignment, contrary to the effect of pointlike defects. Based on common-sense arguments, one would expect recovery of lines from pancakes at sufficient concentration of CD. Experimental data show that the situation in heavy-ion-irradiated layered compounds is, however, more complicated.

Indeed, resistivity measurements in Bi- and Tl-based high-temperature superconductors (HTS) with columnar defects aligned along the $c$ axis[7,8] show that at low temperatures the irreversibility line is uniaxially enhanced when the magnetic field is applied parallel to the CD axis and that scaling with the $c$-axis component of the field is absent at small angles between the magnetic field and the $c$ axis, indicating stronger $c$-axis correlations in the liquid phase as compared with the unirradiated crystals.

On the other hand, in magnetic fields, $B$, well below the matching field $B_\phi$, and at temperatures several K below $T_c$, the reversible magnetization $M_{rev}$ exhibits a crossing point[9,10] ($M_{rev}$ becomes independent of $B$ at the ''crossing temperature'' $T^*$) indicating the reappearance of the pancakes in the liquid phase, pancakes being positioned randomly *within* the columnar defects in each layer independently.[11]

Recent Josephson plasma resonance (JPR) data in Bi-2212 crystals with CD[12,13] confirm the existence of two liquid phases with different $c$-axis correlations in limited temperature interval ($\approx$62–68 K at $B_\phi \geqslant 0.3$ T). They reveal the transition line, $B_{rec}(T)$, separating liquid of pancakes with weak $c$-axis correlations (decoupled liquid [DL]) at $B_{rec}(T) > B > B_{irr}(T)$ and liquid with strong $c$-axis correlations (coupled liquid [CL]) above $B_{rec}$. The *recoupling* line lies above the irreversibility line $B_{irr}$ at which *decoupling* of pancakes occurs as $B$ increases from the Bose-glass phase. The lines $B_{irr}(T)$ and $B_{rec}(T)$ merge at the temperature $T_0$, lying around 60 K, see Fig. 1, where data of Ref. 12 were used. More specifically, JPR measurements[12,13] show that dependence of plasma resonance frequency, $\omega_p$, on $B$ and $T$ is different in the DL and CL phase and $\omega_p$ increases sharply as $B$ approaches $B_{rec}$ from below. Such behavior of $\omega_p$ provides direct evidence on improving alignment of pancakes above $B_{rec}(T)$. Note that at present we do not have sufficient data to discriminate between a true phase transition and a crossover between two kinds of vortex liquid involved.

In this paper we present the qualitative description of the mechanism of the recoupling transition between the pancake-like and linelike vortex liquids in the heavy-ion irradiated anisotropic superconductors within the framework of the model of pancakes localized at columnar defects explored in our earlier work.[11] The transition in question is then the interaction-driven transition from the system of independently trapped pancakes to the state of the trapped pancake stacks or vortex lines as the magnetic field increases. Note that at the irreversibility line the opposite entropy-driven transformation takes place as the field increases: stacks of pancakes trapped inside CD transform into decoupled pancakes still trapped inside CD.

Let us summarize briefly the model of the pancakes in the presence of CD used previously to describe reversible magnetization in layered superconductors (see Ref. 11). Taking the pinning energy of the trapped pancake equal to $-E_p$ and putting the energy of the free pancake equal to zero, we thus introduce the two-level description of the system of pancakes. The pinning energy $E_p$ is of the order $E_0 \ln(R/\xi_{ab})$, where $E_0 = \Phi_0^2 s/16\pi^2\lambda_{ab}^2$, $s$ is the interlayer spacing, $R$ is

 

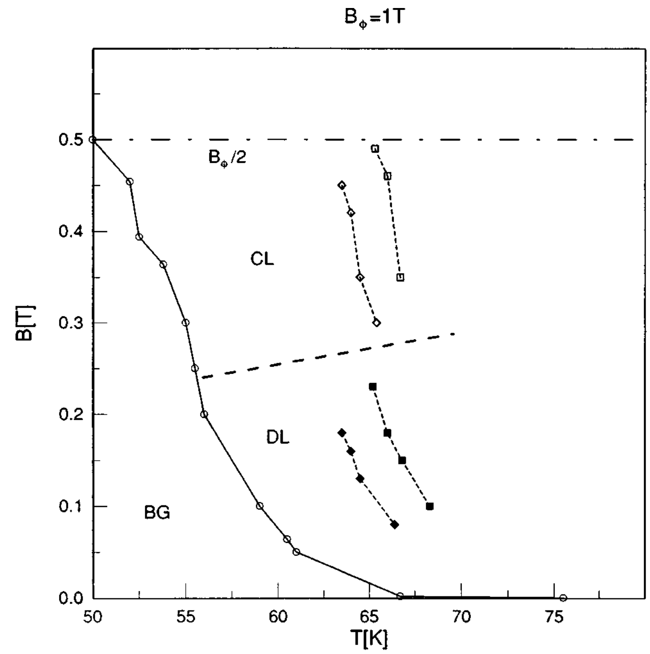


FIG. 1. The phase diagram of irradiated Bi-2212 with $T_c = 85.7$ K at $B_\phi = 1$ T. Circles show irreversibility line obtained from irreversible magnetization measurements with criterion 80 A/cm$^2$ for current along the $ab$ plane. Open squares and diamonds show Josephson plasma resonance magnetic fields in the liquid state with strong $c$ axis correlations at frequencies of 30 and 45 GHz, respectively. Filled squares and diamonds show resonance fields in the liquid with weak correlations. The dashed line shows approximately the recoupling line inferred from JPR data.

the radius of CD, and $\xi_{ab}$ is the superconducting correlation length (see Ref. 14). The concentration of pinning sites is $B_\phi/\Phi_0 s$ (degeneracy of $-E_p$ level), while the concentration of outside sites with the assigned zero energy is $H_f = H_{c2}(T)E_0/2\Phi_0 sT$. We take the elementary area of an outside site equal to $\xi_{ab}^2 T/E_0$ (see Ref. 15). We assume CD parallel to the $c$ axis and neglect the possible dispersion in the CD directions and pinning energy $E_p$. The strong repulsion of pancakes excludes the double occupancy of the sites, this is accounted for by using Fermi statistics for pancakes: the number of pancakes $N_{n\nu}$ that occupied the site $\nu$ in the layer $n$ is 0 or 1.

The decoupling transition is governed by the competition between the entropy gain due to redistribution of pancakes among the different columns and the coupling interaction. To fix the idea let us first neglect the Josephson coupling and consider the system of magnetically interacting pancakes. The energy of the pancake system with pinning inside CD and pairwise magnetic interaction of pancakes[16] is of the form

$$\mathcal{F}_M\{\mathcal{N}_{n\nu}\} = -\sum_{n\alpha} E_p \mathcal{N}_{n\alpha} + \sum_{n\nu \neq n'\nu'} V(n\nu, n'\nu')\mathcal{N}_{n\nu}\mathcal{N}_{n'\nu'}, \tag{1}$$

where index $\alpha$ numerates CD and pancake-pancake interaction is

$$V(n\nu, n'\nu') = \frac{E_0}{4\pi} \int d\mathbf{k} \int_0^{2\pi} dq \, \frac{\exp[i\mathbf{k}(\mathbf{r}_{n\nu} - \mathbf{r}_{n'\nu'}) + iq(n-n')]}{k^2[1 + \lambda_{ab}^{-2}(k^2+Q^2)^{-1}]},$$

$$Q^2 = (2/s^2)(1 - \cos q). \tag{2}$$

Here the integration over $k$ is in the region $0 \leq k \leq \xi_{ab}^{-1}$, and $\mathbf{r}_{n\nu} = (x_{n\nu}, y_{n\nu})$ are the coordinates of site $n\nu$. Magnetic interactions are repulsive within the layer but cause the attraction of pancakes in different layers tending to align pancakes along the $c$ axis.

Consider magnetic fields $B \leq B_\phi$ and temperatures $T \ll E_p$ neglecting for a moment those pancakes that are thermally excited to the free bulk outside of CD. In the Bose-glass state the pancakes are localized at CD. Above the irreversibility line, which marks the delocalization transition, pancakes can jump from one pinning site to another under the applied infinitesimal dc current, so the system exhibits linear response. Note that the linear hopping pancake resistivity in the pancake liquid state resembles strikingly the linear hopping conductivity in the impurity band in semiconductors. This suggests particle-hole symmetry analogous to that in semiconductors: at fields very close to $B_\phi$ the hopping pancake transport can be viewed as the sequence of jumps of *holes* from one column to another, the holes are the empty sites on CD *not occupied* by pancakes.

To verify the picture and explore the consequences let us examine the behavior of the free energy of Eq. (2) under the transformation $\mathcal{N}_{n\alpha} \Rightarrow 1 - \mathcal{N}_{n\alpha}$, when we replace pancakes by holes. Here we use subscript $n\alpha$ to label pancake inside columnar defect $\alpha$ in layer $n$. We obtain

$$\mathcal{F}_M\{1-\mathcal{N}_{n\alpha}\} = F_0 + \sum_\alpha \left( E_p - 2E_0 \times \sum_{\alpha'(\neq\alpha)} K_0(|\mathbf{r}_\alpha - \mathbf{r}_{\alpha'}|/\lambda_{ab}) \right) \mathcal{N}_\alpha + \sum_{n\alpha \neq n'\alpha'} V(n\alpha, n'\alpha')\mathcal{N}_{n\alpha}\mathcal{N}_{n'\alpha'},$$

$$\mathcal{N}_\alpha = \sum_n \mathcal{N}_{n\alpha}. \tag{3}$$

Here $\mathbf{r}_\alpha$ are coordinates of CD, and $K_0(x)$ is the McDonald function, $K_0(x) = \int_1^\infty du(u^2-1)^{-1/2} \exp(-xu)$.

Note that if the term with the McDonald function on the right-hand side of Eq. (3) coming from interaction of pancakes inside randomly positioned CD was $r_\alpha$ independent, the energy would have exhibited the exact particle-hole symmetry. Then delocalization of holes will be exactly the same as for pancakes, i.e., the second delocalization line, $B_{sym}(T) = B_\phi - B_{irr}(T)$ would exist which is mirror symmetric to the line $B_{irr}(T)$ with respect to the line $B = B_\phi/2$. The way it is, our system of pancakes at $B_\phi/2 < B < B_\phi$ with hole concentration $(B_\phi - B)/\Phi_0 s$ is equivalent to the system of pancakes in magnetic field $(B_\phi - B)$ with the functional (1) where the pinning energy in the CD labeled by $\alpha$,

$$E'_p(\alpha)=E_p-V_\alpha+\langle V_\alpha\rangle, \tag{4}$$

$$V_\alpha=2E_0\sum_{\alpha'(\neq\alpha)}K_0(|\mathbf{r}_\alpha-\mathbf{r}_{\alpha'}|/\lambda_{ab}), \tag{5}$$

should be replaced for $E_p$. Here $\langle V_\alpha\rangle$ is the average of $V_\alpha$ over $\alpha$ or over disorder in CD positions. Let us assume that $T\ll E'_p(\alpha)$. Then one can conjecture that as the field approaches $B_\phi$ *the holes get localized and aligned* above the field $B_{sym}(T)=B_\phi-B'_{irr}(T)$ analogously to the localization and alignment of pancakes below the irreversibility line. The field $B'_{irr}(T)$ behaves similarly to $B_{irr}(T)$ up to the renormalization of the characteristic energies due to change in effective pinning energy [Eq. (4)]. Thus the second transition line $B_{sym}(T)$ appears and both lines, $B_{irr}$ and $B_{sym}(T)$ merge at temperature $T_0$ where $B_{irr}=B_{sym}=B_\phi/2$.

Now we show that Josephson interlayer coupling alone possesses the exact particle-hole symmetry provided that all the pancakes occupy CD. The functional describing this interaction may be written in terms of occupation numbers $\mathcal{N}_{n\nu}$ and gauge-invariant phase differences $\varphi_n^{(v)}(\mathbf{r})+\varphi_n(\mathbf{r})$ between layers $n$ and $n+1$ (see Ref. 17):

$$\mathcal{F}_J\{\mathcal{N}_{n\nu},\varphi_n\}=(E_0/2\pi)\int d\mathbf{r}\Bigg\{\sum_{nn'}L_{nn'}\nabla\varphi_n\nabla\varphi_{n'}+\frac{2}{\lambda_J^2}[1-\cos(\varphi_n^{(v)}+\varphi_n)]\Bigg\}. \tag{6}$$

The first term is the energy of intralayer currents with the inductive matrix

$$L_{nn'}=\frac{\lambda_{ab}}{2s}\left(1-\frac{s}{\lambda_{ab}}\right)^{|n-n'|}. \tag{7}$$

The second term is the Josephson interlayer energy and $\lambda_J=\gamma s$ is the Josephson length, $\gamma$ is the anisotropy parameter. The term $\varphi_n^{(v)}(\mathbf{r})$ is the phase difference between layers $n$ and $n+1$ induced by pancake vortices in these layers when Josephson coupling is absent, $\lambda_J=\infty$:

$$\varphi_n^{(v)}(\mathbf{r})=\sum_\alpha[\mathcal{N}_{n\alpha}f(\mathbf{r}-\mathbf{r}_{n\alpha})-\mathcal{N}_{n+1,\alpha}f(\mathbf{r}-\mathbf{r}_{n+1,\alpha})],$$
$$f(\mathbf{r})=\arctan(x/y). \tag{8}$$

Here $\mathbf{r}=(x,y)\perp c$. The term $\varphi_n(\mathbf{r})$ in the total phase difference accounts for screening by Josephson currents. The phase $\varphi_n(\mathbf{r})$ can be integrated out resulting in the functional depending only on the pancake coordinates. The induced interaction of pancakes is multiwise due to nonlinearity of the functional with respect to the phase difference. As magnetic interaction, it also tends to align vortices along the $c$ axis.

Upon replacement $\mathcal{N}_{n\alpha}\Rightarrow 1-\mathcal{N}_{n\alpha}$ we get

$$\varphi_n^{(v)}(\mathbf{r})=\sum_\alpha[f(\mathbf{r}-\mathbf{r}_{n\alpha})-f(\mathbf{r}-\mathbf{r}_{n+1,\alpha})]-[\mathcal{N}_{n\alpha}f(\mathbf{r}-\mathbf{r}_{n\alpha})-\mathcal{N}_{n+1,\alpha}f(\mathbf{r}-\mathbf{r}_{n+1,\alpha})]. \tag{9}$$

The first term on the right-hand side vanishes because $\mathbf{r}_{n\alpha}=\mathbf{r}_{n+1,\alpha}$ and the change of sign in the second term is unimportant because we may change the sign of $\varphi_n$. Thus the Josephson part of pancake interactions does not change our conclusion about the existence of the second transition line near $B_\phi$.

We associate the second transition line, $B_{sym}(T)$, with the *recoupling line* $B_{rec}$. The region above $B_{rec}(T)$ is the CL phase and the domain between $B_{irr}(T)$ and $B_{rec}(T)$ is the DL phase. The liquid phase here consists of pancakes distributed almost independently in each layer over the columnar defects and able to hop between the pinning sites in response to an infinitesimal driving current. At temperatures below $T_0$ the DL phase does not exist.

Now we discuss the formation of the liquid phase above $B_{rec}$. Remember that there are always pancakes *outside* the CD. Their concentration, although low at small $B$, increases as $B$ grows and raises most dramatically near $B_\phi$, see Ref. 11, yet the density of these untrapped pancakes is small even at this field when $T\ll E_p$ (see above). Therefore, outside pancakes affect weakly the localization of pancakes occupying CD if $E_p\gg T,E_0$, but being delocalized they give a substantial contribution to the vortex transport and give rise to linear dissipation destroying the superconductivity. We assume that at $T>T_0$ they are localized below $B_{irr}$ but remain delocalized above $B_{rec}$ though pancakes trapped by CD become localized above $B_{rec}$. At temperatures below $T_0$, at $B>B_\phi$ untrapped pancakes control the irreversibility line. Since pancakes actually trapped by the columnar defects stay aligned, they induce $c$-axis correlations also on the pancakes placed in the interstitial positions giving rise to a liquid state formed by vortex lines above $B_{rec}$.

Let us summarize the results of the two-level consideration of CD in the limit $E_p\gg E_0,T$. There are three phases in this model:

(a) Low-temperature superconducting Bose-glass phase with frozen aligned vortices inside and outside of CD. In pristine crystals there is a line, $B(T)=B_d$ ($B_d\approx 400$ G), separating the $c$-axis correlated vortex glass and the uncorrelated one (see Ref. 18). Such a line may exist also in crystals with CD, but here $B_d$ probably lies well above $B_\phi$ because there the effect of CD vanishes.

(b) Decoupled pancake liquid phase DL with $c$-axis uncorrelated pancakes inside and outside of CD.

(c) Coupled liquid phase CL with inside linelike correlated almost frozen vortices and aligned mobile outside vortices.

Along the recoupling line $B$ increases with $T$ when $B<B_\phi$, because the gain in entropy in the DL phase diminishes as $B$ approaches $B_\phi$. The recoupling line turns around and becomes a decoupling line at temperatures where pinning is ineffective. At larger $B$ along this decoupling line, temperature drops with $B$ because pinning provided by CD becomes less effective as $B$ increases and the vortex system approaches that in the pristine crystal.

The above two-level scenario of strong pinning provides a consistent explanation of resistivity, JPR, and reversible magnetization data. However, a good quantitative agreement between this simplified model and the experimental data is still lacking. For example, our model predicts that merging temperature $T_0$ would correspond to the field $B=B_\phi/2$ for the recoupling line DL-CL, while they merge at $B\approx 0.25B_\phi$.

The discrepancy is caused primarily by the combined effects of vortex interactions and disorder in CD positions when the pinning energy, $E_p$, is comparable with interaction energy, $E_0$. Then $V_\alpha$ in Eq. (4) for high matching fields has quite large variance, $\langle V_\alpha^2\rangle - \langle V_\alpha\rangle^2 = E_0^2 B_\phi \pi \lambda_{ab}^2/\Phi_0$. Thus for some columnar defects $E_p'$ is negative. This means that, as magnetic field increases, it is more favorable for some pancake vortices to occupy positions between CD in the regions where the concentration of CD is well below average (see Refs. 19 and 20). In this case the gain in the interaction energy of vortices may exceed the loss of pinning energy. This effect leads to a drop in effective pinning energy with magnetic field and to an increase in the concentration of outside vortices in fields well below $B_\phi$. As a result, $B_{rec}$ decreases, and the magnetic field where lines $B_{irr}$ and $B_{rec}$ merge at $T_0$ also decreases and lies below $B_\phi/2$ when pancakes are positioned randomly.

For periodically arranged CD one gets $E_p'=E_p$ because $V_\alpha - \langle V_\alpha\rangle = 0$. Here violation of particle-hole symmetry is caused by pancakes thermally excited to sites outside of CD. Then deviations of $B_{rec}$ from $B_\phi - B_{irr}$ are exponentially small, $\propto \exp(-E_p/T)$, at $T \ll E_p$.

In conclusion, we use particle-hole symmetry for pancake interactions inside CD in irradiated superconductors to show that in addition to a transition at the irreversibility line, there is another transition for vortices trapped inside CD at high enough temperatures and in magnetic fields below $B_\phi$. This gives a natural qualitative explanation for the occurrence of two liquid phases with stronger and weaker $c$-axis correlations of pancake vortices. For randomly positioned CD our description of the recoupling transition is only qualitative. Our quantitative prediction about the position of the recoupling transition is accurate for periodically arranged CD with strong pinning.

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