Nonlocal screening in a vortex line liquid

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The recent experiments[1] reporting the onset of the nonlocal conductivity in the vortex state of YBaCuO single crystals indicate that a new liquid phase of vortices is present. This phase is intermediate between the normal metal and the Abrikosov lattice. The mapping of the vortex problem to the problem of Bose liquid issued to determine theoretically the properties of the proposed vortex liquid phase. These properties are compared with the data. © *1995 American Institute of Physics.*

In a recent letter Safar *et al.*,[1] reported the results of transport measurements in the mixed state of YBaCuO single crystals with the field applied along the c direction of the crystal, performed in a transformer geometry (Fig. 1). Two sets of measurements were done. In the first one, the current was injected through the pair of contacts (1,4) and the potential was measured between contacts (2,3) or (6,7). In the second set, the current was injected through contacts (1,5) and the potential was measured between contacts (2,6), (3,7) or (4,8). In the first setup, the current flows predominantly in the ab plane of the crystal, while in the second setup the current flows mostly in the c direction.

It was found[1] that in the first setup the potential drop between contacts (6,7) is smaller than the drop between (2,3) at high temperatures, but becomes undistinguishable from it below a critical temperature T_{th}. If this observation is interpreted in terms of the apparent resistivity ratio ρ_c/ρ_{ab}, it implies that this ratio tends to zero at $T\to T_{th}(H)$. This temperature $T_{th}(H)$ is significantly higher than the transition temperature $T_g(H)$ defined by $\rho_{ab}(T_g)=0$. The experiments of the second setup showed, however, that the ratio of the potentials V_{48}/V_{26} becomes much *larger* when $T\to T_{th}(H)$, indicating that the apparent ratio ρ_c/ρ_{ab} extracted from these measurements tends to infinity. Finally, an independent set of measurements indicate that the resistivity in the c direction extracted from measurements with the uniform current is[2] $\rho_c(T_{th})=0$.

Safar *et al.*[1] interpreted their results as evidence for nonlocal transport in the mixed state: In this note we shall show that this nonlocal transport may be the signature of a phase transition to the novel vortex liquid state characterized by a nonzero phase rigidity in the direction of the magnetic field.[3,4] We argue that T_{th} should be identified with the transition temperature to the intermediate vortex liquid state.

We begin with the estimates of the parameters of the vortex system in the regime of the experiments.[1,2] We use the value of the penetration length $\lambda=1400$ Å and the anisot-

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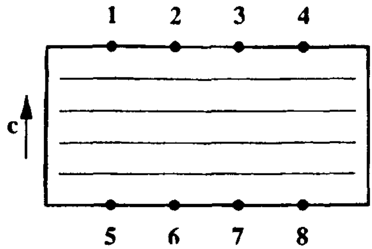

FIG. 1.

ropy ratio $M/m=50$ to estimate a vortex entanglement length (cf. Ref. 5) in the c direction: $L=1.5(1-t)/B$ μm, where $t=T/T_c$, and B is measured in Tesla, which gives $L\sim 0.03$ μm under the conditions of Refs. 1 and 2. Thus, the vortices are entangled on a much shorter scale than the sample thickness (0.03 mm). This estimate rules out the simple explanation of the experiment[1] that each individual vortex remains straight on the scales of the sample thickness. The absence of a current dissipation in the c direction shows that, although the vortices wander at short scales, they remain relatively straight at large scales due to the collective effects. The dissipation of the uniform in-plane current shows that the vortex lattice is not formed.

In order to describe the state of the liquid of vortices quantitatively, we mapped the vortex problem to the model of strongly interacting two-dimensional bosons.[4] We showed that the problem of the Gibbs equilibrium state of the system of infinitely long vortices at temperature T is formally equivalent to the quantum ground-state problem of the interacting two-dimensional Bose liquid (with the "2D Plank constant" $\hbar_{2D}=T$) at zero temperature. The direction of the vortex space along the magnetic field ($\hat{\mathbf{z}}\|\mathbf{c}$) plays the role of imaginary time of the 2D quantum theory. The interaction between bosons in the quantum model has two parts: static 2D Coulomb part and dynamic transverse current–current interaction mediated by the fluctuating 2D "magnetic" field (cf. Refs. 3 and 4). This mapping identifies the Abrikosov lattice and the crystal of bosons, the normal metal, and the Bose superfluid liquid. In Ref. 4 we also found a new vortex liquid phase between the Abrikosov lattice and the normal metal, which is mapped into the "normal" (i.e., nonsuperfluid) liquid of bosons. Here we use this mapping to find the response of the vortex phase under the conditions of the experiment of Ref. 1. In Refs. 3 and 4 we derived the duality relations between the response functions in the vortex system and the response function for the boson system. We found that the new intermediate phase has nonzero superfluid density in the c direction: $j_c=-n_s^{cc}A_c$, and that it has a finite resistivity to the *uniform* current in the ab directions. The (normal metal)–(new phase) phase transition line predicted in Ref. 4 (Fig. 1a) is surprisingly close to the $T_{th}(H)$ line reported in Refs. 1 and 2. Below we show that in this state the *nonuniform* in-plane current, which satisfies $\int j_{ab}dz=0$, is nondissipative. This resolves the apparent contradiction of observations, because in the setup yielding $\rho_{ab}/\rho_c\to 0$ the in-plane current $\int j_{ab}dz=0$.

We prove the existence of a nondissipative current $j_{ab}(q_z\neq 0)$ repeating the derivation of the response functions (cf. Sec. VI.A.1 in Ref. 4) for the in-plane currents

$$D(q)=\langle A_a(q)A_a(-q)\rangle=\frac{4\pi T}{q^2+\mathscr{P}_{\|}(q)};$$

$$\mathscr{P}_{\parallel}(q)=\frac{1}{\lambda^2}\frac{q_z^2}{q^2+g^2\Pi_{\parallel}(q)}, \tag{1}$$

where $\Pi_{\parallel}(q)$ is the longitudinal response of the dual Bose liquid, and $g^2=\phi_0^2/4\pi\lambda^2$ is its interaction constant, i.e., the analog of the electric charge e_{2D}. Here and below we explicitly consider only isotropic superconductors; we shall restore the anisotropy factor m/M only at the very end, using the general scaling arguments.[6]

The intermediate phase corresponds to the normal liquid of bosons. Since q_z plays the role of the frequency in the Bose model, $\Pi_{\parallel}(q)$ is strongly dependent on the ratio $q_z/q_\perp$. In the limit $q_\perp\to 0$, the longitudinal response of the boson system is described by the finite effective "conductivity" σ: $g^2\Pi_{\parallel}(q_z)=\sigma|q_z|$ To estimate the effective conductivity, we note that the normal Bose liquid is realized in the regime of the strong interaction, when the dimensionless interaction parameters are on the order of unity.[4] In this regime the only combination of parameters with the dimensionality of conductivity is the "quantum" conductivity, $\sigma_Q=e_{2D}^2/h_{2D}$. Identifying $g\to e_{2D}$, $T\to\hbar_{2D}$, we estimate $\sigma\sim g^2/2\pi T$. Using this expression for $\Pi_{\parallel}(q_z)$, we obtain the correlator of the in-plane electromagentic vector potential

$$D(q_z)=\frac{4\pi T}{q_z^2+\Lambda^{-1}|q_z|}, \tag{2}$$

where $\Lambda=\lambda^2\sigma=\Phi_0^2/8\pi^2T$.

Equation (2) shows that the in-plane magnetic field decays at large distances ($z\gg\Lambda$) as $B(z)B_0(\Lambda/z)$ in this state; it is screened on a scale of Λ by a nondissipative current $j\sim(\Lambda/z)^2$ along the boundary. To see this situation, let us consider the effect of the external current flowing in the x direction at the edge of a sample, $j_x^{\text{ext}}(z) = J^{\text{ext}}\delta(z)$. According to Eq. (2), it induces a magnetic field $B_y(q_z)=q_z\times D(q_z)\times J^{\text{ext}} \propto 1/[q_z+\text{sgn}(q_z)\Lambda^{-1}]$. After integration over q_z, we obtain the induced field $B_y(z)\sim B_0(\Lambda/z)$ and the shielding current $j_x(z)\propto dB_y/dz$. Note that in the superfluid phase of the Bose liquid we have $\sigma\propto 1q_z$ and $\Pi_{\parallel}(q_z)\sim$const. The electromagnetic correlation function will therefore have its usual form for a normal metal, $D(q_z)\propto q_z^{-2}$. The universal length scale Λ is about 400 μm at $T=90$ K, which is larger than the sample thickness d (note that the rescaling,[6] with allowance for the anisotropy, does not affect the relationship between Λ and d, since both quantities scale the same way). The existence of nondissipative in-plane current at $q_z\neq 0$ in the vortex liquid implies that $\rho_{xx}(q_z\neq 0)=0$ at $T<T_{th}(H)$. We interpret observations[1,2] as a signature of the vanishing of $\rho_{xx}(q_z\neq 0)$ as $T\to T_{th}(H)^+$, which supports a phenomenological description proposed in Ref. 7.

Equation (2) for $D(q_z)$ was derived in the limit of the in-plane homogeneous current, i.e, $q_\perp\to 0$. Using the conventional diffusion form for the density–density correlator

$$\Pi_{\parallel}(\mathrm{q})\sim\frac{\sigma q_z^2}{|q_z|+\mathscr{D}q_\perp^2},$$

we see that Eq. (2) remains valid if the condition $q_\perp^2\ll q_z/\mathscr{D}$ is satisfied. Here $\mathscr{D}$ has the meaning of "diffusion coefficient" which is associated with the conductivity σ. We thus have $\sigma \approx e_{2D}^2 \mathscr{D}(m_{2D}/2\pi\hbar_{2D}^2)$, where the last factor in parentheses is the density of states of the 2D particles with a mass $m_{2D}=(\Phi_0/4\pi\lambda)^2$. The "quantum-limit" expression for σ, which we used above, means that the mean free path of bosons is on the order of their separation; i.e., $\mathscr{D}\approx\hbar_{2D}/m_{2D}$.

Let us now estimate the relative size of the wave vectors q_z and $q_\perp^2$ for the conditions of the experiment.[1] After the rescaling,[6] taking into account the mass anisotropy factor $m/M=0.02$, the relevant wave vectors become $q_z \approx \sqrt{m/M}/d$, $q_\perp \approx 1/d_{\rm plane}$, with the sample thickness $d=(3-6)\times 10^{-3}$ cm and the relevant lateral dimension $d_{\rm plane}\approx 0.05$ cm. With the above estimates for $\mathscr{D}$, the condition $q_\perp^2 \ll q_z/\mathscr{D}$ is satisfied for any reasonable sample size.

We expect that the results of the dc transformer measurements in thick samples $(d>\Lambda)$ should be qualitatively different from the samples reported in Refs. 1 and 2, because of the screening effects. Finally, we note that the results obtained in twinned samples for the tilted field are severely modified by the interaction between vortices and twins, because under these conditions each vortex line intersects the twin boundary, which affects strongly the motion and equilibrium positions of vortex lines.

In conclusion, the observations in Refs. 1 and 2 strongly support the existence of a new vortex line liquid state which is sandwiched between the normal state and the vortex glass.

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