Upper Limit of the Bose-Glass Transition in $YBa_2Cu_3O_7$ at High Density of Columnar Defects

A. V. Samoilov,[1,*] M. V. Feigel'man,[1,2] M. Konczykowski,[1] and F. Holtzberg[3]
[1]*Laboratoire des Solides Irradiès, Ecole Polytechnique, 91128 Palaiseau, France*
[2]*L. D. Landau Institute for Theoretical Physics, 117940 Moscow, Russia*
[3]*Emeritus IBM, Thomas J. Watson Research Center, Yorktown Heights, New York 10598*
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The Bose-glass transition in $YBa_2Cu_3O_7$ single crystals with columnar defects produced by irradiation with 5.8 GeV Pb ions was studied both experimentally and theoretically. The Bose-glass transition line $B_{\rm BG}(T)$ progressively shifts upwards with increasing doses of irradiation ϕ, up to 10^{11} ions/cm^2. For larger ϕ, the $B_{\rm BG}(T)$ line does not shift anymore, and saturates at $B_{\rm BG}^{\rm max}(T)$, which is still considerably below $H_{c2}(T)$. Theoretically, we show that the observed evolution of the Bose-glass transition line provides strong evidence for an *intermediate* or *disentangled* vortex liquid phase, sandwiched between the melting line $B_m(T)$ and $B_{\rm BG}^{\rm max}(T)$, in *virgin samples*.

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The nature of the vortex liquid state attracted considerable attention over past years [1]. This problem can be conveniently considered by mapping it [2] onto the problem of a 2D quantum Bose liquid. In this analogy, the vortices correspond to the world lines of bosons. In other words, the length along the direction of magnetic field in the original superconductor corresponds to imaginary time for the case of bosons, whereas the temperature T corresponds to the Planck constant $\hbar_B$ of the Bose system. It was suggested theoretically [3,4] that the vortex liquid may exist in two different thermodynamic phases: the *entangled* phase [2], macroscopically equivalent to the normal metal [3], and the *disentangled* phase, which possesses superconductive coherence along the direction of magnetic induction $\mathbf{B}$ [3,4] in spite of the absence (due to thermal melting) of crystalline ordering of vortices. Within the mapping onto 2D bosons, the disentangled phase is analogous to the normal (nonsuperfluid) ground state of Bose liquid, where the world lines are well defined for each individual boson. The entangled phase corresponds to the superfluid ground state where the discrete nature of individual particles is indistinguishable due to strong exchange effects. Within such a picture there exist *two* phase transitions between the normal metal and a classical vortex lattice: the melting transition at $B = B_m(T)$ and the decoherence transition at $B = B_d(T) > B_m(T)$. Experimentally the $B_d(T)$ should be discernible by the disappearance of the electric resistivity $\rho_\parallel$ for electrical current $\mathbf{j} \parallel \mathbf{B}$, and some data [5,6] indeed seem to indicate [7] the existence of such a $B_d(T)$ line in clean $YBa_2Cu_3O_7$ (YBCO) single crystals.

Introduction of columnar defects into high temperature superconductors (HTSC) results in the appearance of a new line in the phase diagram of the vortex state: that of the Bose-glass (BG) transition at $B = B_{\rm BG}(T)$ which is characterized by zero vortex mobility. Contrary to the vortex-glass transition line in virgin HTSC crystals, the Bose-glass transition line is expected [8] to lie substantially above the melting line $B_m(T)$ (if the density of columnar defects is sufficiently high). Theoretically, this transition was predicted by Nelson and Vinokur [8] who mapped this problem onto the 2D Bose liquid in the static random potential. (The columnar defect potential is expected to be homogeneous along the defect direction, which coincides with the direction of $\mathbf{B}$, therefore the mapping onto the 2D problem is possible.) Experimentally, significant pinning enhancement after bombardment of YBCO superconductor with swift heavy ions, resulting in creation of linear tracks over the whole sample thickness, was reported in earlier work by Konczykowski *et al.* [9] and by Civale *et al.* [10] (see also Ref. [11]).

The open question (from both experimental and theoretical points of view) is: What limits the shift of the BG line to higher temperatures (T) and magnetic fields (H) with increasing defect concentration? An ultimate limit for $B_{\rm BG}^{\rm max}(T)$ is imposed by the upper critical field $H_{c2}(T)$ [1] at which the amplitude of the superconducting order parameter vanishes. However, the $H_{c2}(T)$ line, as a mean-field theory result, seems to be a gross overestimate: The order-parameter fluctuations in HTSC are rather strong and may result in a considerable downward shift of the $B_{\rm BG}^{\rm max}(T)$ line. In this paper we present experimental data on YBCO single crystals and theoretical arguments relating $B_{\rm BG}^{\rm max}(T)$ with the $B_d(T)$ transition line of the virgin material.

The progressive shift of the Bose-glass temperature $T_{\rm BG}$ with increasing matching fields $B_\Phi = \Phi_0\phi$ (at $B = B_\Phi$, the number of vortices matches the number of defects; $\Phi_0 = hc/2e$ is the flux quantum) for $B_\Phi \leq 20$ kG is in agreement with theory [8] as reported previously [12]. The novel observation here is that for $B_\Phi \geq 20$ kG, $T_{\rm BG}$ does not increase with increasing dose, indicating that there is an upper limit for the BG transition line $B_{\rm BG}^{\rm max}(T)$. We show that this observation lends support to the idea of the existence of the disentangled vortex phase in the virgin YBCO crystals. In effect, we suggest that the $B_{\rm BG}^{\rm max}(T)$ line is the disentangled-entangled

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transition for undamaged YBCO (which, as our estimates show, does not shift itself with an increasing number of defects). The order of our theoretical consideration will be as follows: First, we will show that in the considered (T, H) range, vortex-defect interaction energy is small as compared to both vortex-vortex interaction energy and kT (k is the Boltzmann constant). Hence an adequate description of the system should start from the picture of a dense, strongly interacting vortex liquid. Second, we will argue that this liquid needs to be *disentangled* in order for irradiation to produce a shift of the Bose-glass line.

Our samples are YBCO single crystals, typically $500 \times 500 \times (25-30)\ \mu$m in size, with the c axis along the smallest dimension. They were irradiated along the c axis with 5.8 GeV Pb ions at the Grand Accélérateur National d'Ions Lourds (Caen, France). The irradiation of YBCO with heavy ions is known to produce continuous tracks of amorphous material of diameter ~70 Å [9,10,13]. The number of columnar defects equals the number of incident ions. We have measured seven samples irradiated with doses of $\phi = 5 \times 10^9 - 2.7 \times 10^{11}$ ion/cm^2. Thus the range of the matching field B_Φ for our samples was 1000–54 000 G. The superconducting zero-field transition temperature T_c for all the samples is 92–93 K. A system of two pairs of coils, defocusing the ion beam in two directions perpendicular to the direction of the beam, was used to homogeneously irradiate the samples. The maximum suppression of T_c after irradiation (for $B_\Phi = 54$ kG) was ~0.7 K. We track the Bose-glass transition by the onset temperature of the third harmonic generation T_{χ_3} with the use of the local Hall probe magnetometer [14]. In this method, a Hall probe is placed on the top surface of the sample, near the center, to pick up an ac signal measured by a lock-in amplifier. The dc magnetic field was produced either by a homemade superconducting coil (for the low-dose samples), or by an electromagnet (for the high-dose samples), or by a Cryogenic 8 T superconducting coil ($\phi = 2 \times 10^{11}$ ions/cm^2). Both ac and dc fields were parallel to the c axis. The onset of the third harmonic marks the onset of a nonlinearity, which, in the system with columnar tracks, is the Bose-glass transition [8]. As we have discussed in Ref. [12], the choice of T_{χ_3} for tracking the BG transition is justified (i) by the absence of the f and $h_{\rm ac}$ dependences of the onset (f and $h_{\rm ac}$ are the frequency and amplitude of the ac field) at low f and $h_{\rm ac}$ used in our experiment ($h_{\rm ac} = 0.1-1.5$ Oe and $f = 1-7$ Hz) and (ii) by the sharpness of the onset as exemplified in the inset of Fig. 1. The main frame of Fig. 1 shows a progressive shift of the BG transition with the irradiation dose, starting from $B_{\rm BG}(T, B_\Phi = 1\ {\rm kG}) \cong B_m(T)$ at lowest dose ϕ. Except for the initial part of the $B_{\rm BG}(T)$ curves near the T_c, the dependences $B_{\rm BG}(T)$ are close to linear at all doses, both above and below the matching field. As shown in Ref. [12], the linear slope is proportional to $1 + \alpha B_\Phi^{1/2}(T)$ (α is a constant, in agreement with the theory [1,15]); see also Fig. 2, inset.

Our main experimental result is presented in Fig. 2 where we plot the BG lines for the high-dose samples (the highest matching field was 54 kG; at higher doses the T_c is known to vanish dramatically). The increase of the dose above 10^{11} ions/cm^2 ($B_\Phi = 20$ kG) does not result in a further upward shift of the BG transition line. This effect is further illustrated in the inset to Fig. 2 where the slope $dB_{\rm BG}(T)/dT$ is seen to saturate at $B_\Phi \approx 20$ kG In other words, *there exists an upper limit [which is still much below $H_{c2}(T)$] of the upwards shift of the BG transition in YBCO with increasing concentration of columnar pins*. We will argue that this upper limit can be

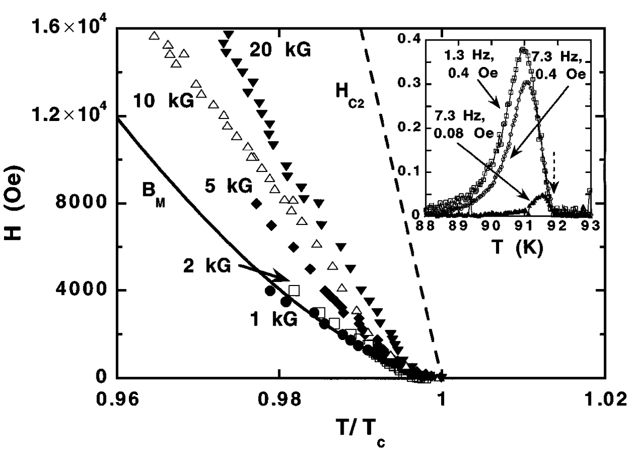

FIG. 1. Progressive upward shift of the Bose-glass transition lines with increasing track concentration (for matching fields $B_\Phi \leq 20$ kG as indicated near the curves). The solid and dashed lines are those for melting, $B_M(T)$ [19], and for $H_{c2}(T)$ [1]. Inset: The third harmonic signal at different frequencies and amplitudes of the ac field ($H = 100$ Oe, $B_\Phi = 54$ kG). The vertical dashed arrow shows the (f- and $h_{\rm ac}$-independent) onset T_{χ_3}.

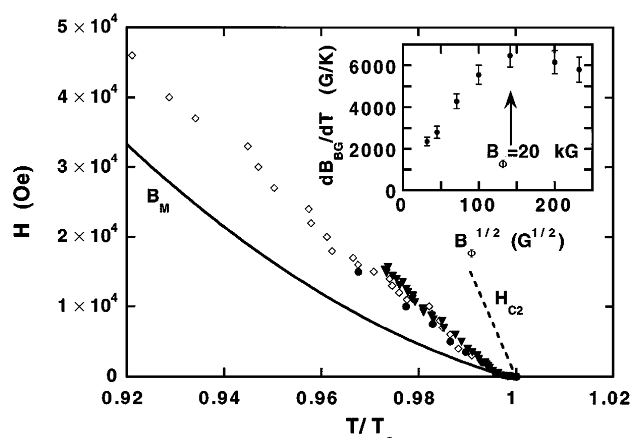

FIG. 2. The Bose-glass transition lines for $B_\Phi \geq 20$ kG. The data for $B_\Phi = 20$ kG represent the maximum possible shift of $B_{\rm BG}(T)$. Inset: The dependence of the linear slope of the BG transition on $B_\Phi^{1/2}$.

indicative of the disentangled-entangled transition in the vortex liquid phase for *unirradiated* YBCO.

First of all, we show that the interaction of a single vortex with a single columnar defect (SV-SD) is extremely weak in the temperature range $1 - T/T_c \leq 0.035$ where most data are recorded. There are two factors responsible for the weakness of this interaction: (i) At these temperatures the coherence length $\xi(T)$ becomes longer than the mean radius of the columnar defects $r_r \approx 3.5$ nm, which makes the "bare" value of the pinning energy rather low; and (ii) thermal fluctuations of the vortex line are very strong and lead to an exponential suppression of the effective pinning energy with respect to its bare value. Quantitative analysis of these effects was given in Chap. 9 of [1] [cf. Eqs. (9.67)–(9.70)] and leads to the following expressions for the pinning energy density $\epsilon_{\rm pin}(T)$ and the for the mean-squared amplitude of thermal fluctuations of the vortex on a defect (i.e., "localization length") $\langle u^2(T)\rangle^2 = l_{\rm loc}(T)$:

$$\epsilon_{\rm pin}(T) = \frac{\epsilon_0 r_r^2}{4\xi^2(T)}\, e^{-T/T_1}, \quad l_{\rm loc}(T) = \xi(T)\,\frac{T}{T_1}\, e^{T/2T_1} \tag{1}$$

valid for $T \geq T_1 \approx \epsilon_0 r_r/\pi\gamma$; here $\epsilon_0 = [\Phi_0/4\pi\lambda(T)]^2$, the anisotropy factor of penetration depths $\lambda_c/\lambda = \gamma$ is about 5–7 for the YBCO compound. One finds [16] the ratio $T/T_1 \geq 8$ in the temperature range of our experiments. Thus within the whole range of defect densities the condition $l_{\rm loc} \gg d_r = \phi^{-1/2}$ is fulfilled; i.e., an individual vortex can be pinned (if ever) only by a large number of columnar defects, whereas the SV-SD pinning picture is not self-consistent in our range of parameters.

We turn now to the analysis of single vortex pinning by many columnar defects (SV-MD). Using again results from Ref. [1], Eqs. (9.74) and (9.75), we obtain instead of Eq. (1)

$$\epsilon_{\rm pin}(T) \approx \frac{\epsilon_0 r_r^2}{2d_r^2}\left(\frac{\pi T_1}{T}\right)^2, \quad l_{\rm loc}(T) \approx d_r\left(\frac{T}{\pi T_1}\right)^2. \tag{2}$$

The value of $l_{\rm loc}(T)$ as obtained within the SV-MD picture is much lower (within our range of parameters) than its counterpart from (1), which confirms once more the necessity of taking into account multidefect effects. However, the obtained $l_{\rm loc}(T)$ is still much longer than the intervortex separation $a_0 = \sqrt{\Phi_0/B_{\rm BG}(T)}$. Consequently, the interaction between neighboring vortices is actually stronger than the vortex-disorder interaction. It means that the analysis of the disorder-induced effects should start from the properties of the "clean" vortex liquid as a strongly interacting many-body system.

Let us consider now the properties of entangled vortex liquid. Such a liquid can be mapped onto the 2D superfluid Bose liquid. Then we can estimate the threshold value of the disorder strength necessary to destroy the superfluid ground state and to produce instead the Bose-glass state. We use (with slight modifications) the results of Ref. [17] where a dilute Bose gas subjected to a weak random potential is considered and the depletion of the ground-state superfluid density (n_s) due to disorder is calculated. It is evident from Eq. (19) of Ref. [17] that the main contribution to $n_n = n - n_s$ (n is the total particle density) comes from virtual excitations with momenta $K \sim n^{-1/2}$. In a dense Bose liquid the spectrum differs from that of the Bose gas. The main new qualitative feature is the development of a "roton dip"—spectrum $E(K)$ minimum at $K \approx K_0 = 2\pi/a_0$ with the "roton gap" $E(K_0) = E_{\rm rot}$. Usually $E_{\rm rot}$ is less but of the order of $E_0 = (\hbar_B K_0)^2/2m$, with m the particle mass (which is just the line tension $\epsilon_l = \epsilon_0\gamma^{-2}$ in terms of the vortex problem). However, in the vicinity of the transition into the solid state $E_{\rm rot}$ is expected to decrease and may eventually vanish (if this transition is of the second order). It is easy to check that in our parameter range $\epsilon_{\rm pin}/E_0 \approx 2\frac{B_\Phi}{B}(\frac{T_1}{T})^4 \ll 1$, i.e., the disorder is indeed very weak and may be treated perturbatively. In a more quantitative way, we estimate, using the results from Ref. [17], the relative depletion $n_n/n = 1 - n_s/n$ as [16]

$$\frac{n_n}{n} \approx \frac{B_\Phi}{B}\left(\frac{T_1 m^*}{Tm}\right)^4\left(\frac{E_0}{E_{\rm rot}}\right)^{7/2} \leq \left(\frac{m^*}{m}\right)^4\left(\frac{E_0}{10E_{\rm rot}}\right)^{7/2}, \tag{3}$$

where m^* is the effective mass of the "roton" excitation of the 2D Bose liquid defined (for K near K_0) as $E(K) \approx E_{\rm rot} + (K - K_0)^2/2m^*$. It follows from the estimate (3) that the Bose liquid with not very small values of $E_{\rm rot}$ (or not very large ratio m^*/m) is still superfluid in the presence of disorder (as $n_n/n \ll 1$); i.e., the Bose-glass state is not formed in spite of the presence of defects.

In order to understand the detected shift of the $B_{\rm BG}(T)$ line at B_Φ below 20 kG, we need to assume that the roton gap $E_{\rm rot}$ is at least about a factor of 10 less than its "naive" estimate E_0 (see also Ref. [18]). Small values of $E_{\rm rot}$ mean that the vortex density perturbations with $K \approx K_0$ have a long extension $L_z \sim T/E_{\rm rot}$ along the vortex lines direction, which enhances strongly the interaction of vortices with columnar defects parallel to **B**. Now one can understand the progressive shift of the $B_{\rm BG}(T)$ line with an increase of the disorder strength, if we assume that the roton gap $E_{\rm rot}$, being very narrow in the whole region $B_m(T) < B < B_{\rm BG}^{\rm max}(T)$, still grows with B and/or T increase, so that a larger disorder strength is needed to produce a Bose glass at higher temperatures or fields. However, as we cross the $B_{\rm BG}^{\rm max}(T)$ line, the system's behavior changes radically; i.e., further increase of disorder does not lead to any further shift of the BG line. Thus we think that the $B_{\rm BG}^{\rm max}(T)$ line marks a sudden "jump" of the roton gap $E_{\rm rot}$ from its abnormally small value below this line to much larger (say, of the order of E_0) value above it. The existence of a well-defined change in the behavior of $dB_{\rm BG}(T)/dT$ as a function of

B_Φ at $B_\Phi = 20$ kG (inset to Fig. 2) lends credence to the idea of a sharp phase transition at the $B_{\rm BG}^{\rm max}(T) = B_d$ line in virgin YBCO [18].

Note that the estimate (3) as well as the calculations of Ref. [17] were done for the model Bose liquid with an instantaneous interaction, whereas the correct mapping of the high-density vortex liquid is to be done onto the Bose liquid with a retarded or advanced interaction mediated by an auxiliary 2D electromagneticlike field [4]. Such an interaction (which is not at all weak) leads to the depletion of the roton gap $E_{\rm rot}$ and of the "superfluid density" n_s even in the absence of disorder and may eventually produce [4] a *disentangled* vortex liquid. However, this interaction does not break the translational invariance of the system and thus cannot produce the Bose-glass state in the absence of defects.

Now the whole picture emerging from the preceding discussion may be formulated as follows: (i) In virgin samples strong nonlocal interaction between vortices leads to the formation of the intermediate *disentangled* vortex liquid phase at $B < B_d(T)$; in this phase the "roton gap" $E_{\rm rot}$ is very narrow, and the "boson superfluid density" is $n_s = 0$. (ii) Irradiation-produced disorder, being very weak compared to intrinsic vortex-vortex interaction, is still able, due to the smallness of $E_{\rm rot}$, to localize vortices and produce a Bose-glass state below the dose-dependent line $B_{\rm BG}(T)$. (iii) At $B > B_d(T)$ the vortex liquid is entangled, with large n_s and $E_{\rm rot}$, and disorder cannot affect its properties. In our experiment, we track the $B_d(T)$ as the uppermost position of the BG transition $B_{\rm BG}^{\rm max}(T)$. Additional evidence in favor of the proposed picture comes from comparison with results of Ref. [5]: The $B_{\rm BG}^{\rm max}(T)$ line as obtained from our data is very close to the line $B_{th}(T)$ found in [5], which marks a sudden drop of the c-axis resistivity by almost 2 orders of magnitude, and which is expected [7] to coincide with the theoretical $B_d(T)$ line.

We cannot claim that our present experimental data have proven the existence of a true thermodynamic transition into a disentangled vortex liquid. The observed saturation of $B_{\rm BG}(T)$ might be due to a finite thickness crossover, with the vortices being disentangled on the length scale of the sample thickness below $B_{\rm BG}^{\rm max}(T)$ and entangled above $B_{\rm BG}^{\rm max}(T)$. However, this crossover should be very sharp, which would be nontrivial by itself because the "naive" estimate (i.e., without taking into account the strong-interaction effects) for the entanglement length gives approximately 3 nm [7], i.e., 3 orders of magnitude below the sample thickness.

To conclude, we have shown that the BG transition in YBCO can be shifted upwards only up to a certain limit $B_{\rm BG}^{\rm max}(T)$, which is considerably below the upper critical field $H_{c2}(T)$. For the dose $B_\Phi \approx 20$ kG, the glassy state extends over the largest portion of the H-T diagram, an observation which is important for practical applications. Our theoretical consideration of the Bose-system response to perturbation with disorder demonstrates that the $B_{\rm BG}^{\rm max}(T)$ line separates entangled and disentangled vortex liquids in virgin YBCO.

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*Present address: Condensed Matter Physics 114–36, California Institute of Technology, Pasadena, CA 91125. Electronic address: samoilov@styx.caltech.edu

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