Evidence of Bragg glass phase in high-T_c vortex states with columnar defects

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Abstract

High-T_c vortex states with sparse and weak columnar defects are investigated numerically, and a new phase characterized by Bragg peaks associated with hexagonal symmetry is found. This new phase corresponds to the Bragg glass phase in high-T_c vortex states with point defects. As the number of columnar defects increases, the melting temperature of this new phase also increases owing to “partial trap” of flux lines to columnar defects. The phase transition from the Bragg glass phase to the Bose glass phase occurs when the number of columnar defects further increases. The “interstitial liquid” phase is also observed between these two glass phases and the vortex liquid phase.

Key words: high-T_c vortex state; columnar defect; Bragg glass; Bose glass

Since Nelson and Vinokur formulated[1] high-T_c vortex states with columnar defects in terms of two-dimensional interacting bosons in random potentials,[2] most analytic and numerical studies have been performed along this direction, and the parameter region with strong and dense columnar defects has been mainly considered. Recently a low-density case (10% of strong columnar defects to flux lines) was investigated numerically,[3] and the stability of the Bose glass phase was confirmed. In the present article, we step further. We perform large-scale Monte Carlo simulations with the three-dimensional anisotropic, frustrated XY model on a cubic lattice[4,5]:

$$H = -\sum_{i,j\in ab \text{ plane}} J_{ij} \cos(\phi_i - \phi_j - A_{ij}) - \frac{J}{\Gamma^2}\sum_{m,n\parallel c \text{ axis}} \cos(\phi_m - \phi_n) \ , \qquad (1)$$

$$A_{ij} = \frac{2\pi}{\Phi_0}\int_i^j \mathbf{A}^{(2)}\cdot \mathrm{d}\mathbf{r}^{(2)}, \quad \mathbf{B} = \nabla\times\mathbf{A} \ , \qquad (2)$$

where the periodic boundary condition is applied in all directions. A columnar defect is defined as a set of four weak interactions $J_{ij} = (1-\epsilon)J$ surrounding a plaquette in the ab plane. This plaquette distributes randomly in the ab plane with probability p, and takes the same position along the c axis. Other interactions in the ab plane are given by $J_{ij} = J$. This modeling of columnar defects is a variant of our previous study on point defects.[6] Here we concentrate on the model with the anisotropy $\Gamma = 5$, the density of flux lines $f = 1/25$, and the strength of columnar defects $\epsilon = 0.1$. The system size is $L_a = L_b = 50$ and $L_c = 80$.

Varying temperature (T) and density of point defects (p), we obtain the phase diagram given in Fig. 1. It consists of four phases, namely the Bragg glass (BrG), Bose glass (BG), interstitial liquid (IL) and vortex liquid (VL) phases. The BrG phase was first predicted in vortex states with point defects,[7,8] and is characterized by Bragg peaks of the structure factor associated with hexagonal symmetry originating from the quasi long-

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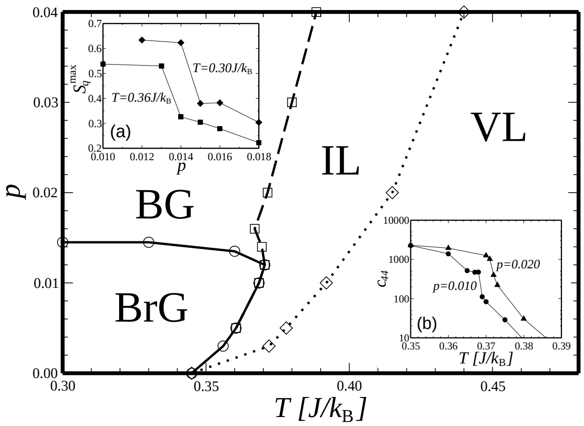

Fig. 1. p–T phase diagram of high-$T_{\rm c}$ vortex states with weak columnar defects described by eq. (1). Defect-density dependence of the maximum value of the structure factor on the BrG-BG phase boundary and temperature dependence of the tilt modulus are displayed in insets (a) and (b), respectively.

range order of flux lines. The boundary of this phase is evaluated by a sudden drop of the maximum value of the structure factor (inset (a) of Fig. 1). Anomalies of thermodynamic quantities such as the specific heat are also seen on the first-order melting line (BrG–IL boundary). In the BG phase, columnar defects are completely occupied by flux lines, and untrapped flux lines do not move around freely owing to interactions with trapped flux lines. The tilt modulus c_{44} is related to the response function $\mu_\perp$ of the transverse magnetization $B_\perp$ to the transverse field $H_\perp$ as $c_{44} \sim \mu_\perp^{-1}$ with $\mu_\perp = \partial \left[\langle B_\perp \rangle\right]_{\rm av} / \partial H_\perp \big|_{H_\perp=0}$.[9] A sharp jump of c_{44} (inset (b) of Fig. 1) signals the BG phase boundary, and this jump becomes infinite in the thermodynamic limit. Note that the jump of c_{44} takes place on the melting line for small p. In the IL phase,[10] part of flux lines are trapped by columnar defects or frozen in the vicinity of trapped flux lines, and other flux lines are freely moving around. The helicity modulus along the c axis Υ_c becomes nonvanishing at the onset of the IL phase. Since weak columnar defects are not completely occupied by flux lines near the IL–VL phase boundary, the BG–IL and IL–VL phase boundaries do not have to meet together at $p/f = 1$ ($p = 0.04$).

The most striking thing of this phase diagram is the existence of the BrG phase even only with columnar defects, which has not been predicted theoretically until present. Although stability of the first-order melting line against very sparse columnar defects was reported in $Bi_2Sr_2CaCu_2O_8$[11] and interpreted by a "pinned carpet" picture, this description does not hold in the present model because p/f is larger than $1/3$ on the BrG–BG phase boundary. In order to clarify the situation, we directly observe how columnar defects trap flux lines, and find that flux lines are trapped *partially* in the BrG phase. That is, only columnar defects suitable for lattice formation trap flux lines, and those apart from lattice positions do not. This indicates that the transition between the BrG and BG phases is determined by the competition of energy gains between lattice formation and complete occupation of columnar defects. Therefore, the position of the BrG–BG phase boundary depends on the strength of columnar defects ϵ. When ϵ increases (decreases), this phase boundary moves toward smaller (larger) p. There may be a critical value $\epsilon_{\rm c}$ above which no BrG phase exists.

This observation explains why the melting temperature $T_{\rm m}$ of the BrG phase increases as the density of columnar defects p increases up to $p \simeq 0.012$. Because of the "partial trap" behavior of flux lines deformation of lattice structure is very small in the BrG phase. Actually, the intensity of Bragg peaks is almost independent of p. The increase of p only results in the energy gain in terms of the number of trapped flux lines and causes the increase of $T_{\rm m}$ as long as the melting transition is induced by thermal fluctuations.

In the melting transition of vortex states, abrupt entanglement of flux lines and sudden increase of dislocations in the ab plane occur simultaneously, and dominance of these two contributions has been discussed. Random columnar defects along the c axis suppress entanglement of flux lines while enhance dislocations in the ab plane. The relation $T_{\rm m} > T_{\rm m}^{\rm pure}$ may suggest that entanglement of flux lines rather than dislocations is the main driving force of the melting transition.

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