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Fluxon Transition in Layered Superconductors and its Role in Dimensional Crossover

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In a layered superconductor, fluctuations of flux loops parallel to the layers result in destruction of the Josephson coupling between layers above a critical temperature T_f. When Fluctuations of point vortices in the layers are included, a 3-dimensional phase transition results at $T_c<T_f$. Study of this fluxon transition shows that variations of T_c as function of anisotropy can be much larger than those in an anisotropic XY model. This can account for the large variations of T_c in multilayers. Furthermore, the fluxon transition can be directly observed, corresponding to the onset of nonlinearity in the c axis I-V relation, as observed in $Bi_2Sr_2CaCu_2O_{8-y}$. This onset is at a higher temperature then the onset of nonlinearity in the ab plane.

1. Introduction

Recent developments in material preparation have led to superlattices[1-3] $(YBa_2Cu_3O_7)_m(PrBa_2Cu_3O_7)_n$. Increasing n, T_c was found to decrease, saturating at[2,3] n=8-16. In particular for m=1, T_c dropped from 90K (n=0) to ~20K (n=16), as in the single layer system[4]. Further experiments[5,6] indicate that variations in interlayer coupling cause the large variation in T_c.

Theoretical data[7,8] on anisotropic XY models show that T_c can change by a factor of 2.4 when going from the 2-dimensional limit to the isotropic 3-dimensional system. Since the effective XY coupling constant τ is proportional to the condensate density which increases upon cooling, the experimental variations in T_c/τ are much larger than 2.4.

The effect of anisotropy on T_c is studied here in terms of the competition between fluctuations of point singularities in each layer, i.e. vortices, and of Josephson flux loops parallel to the layers, i.e. fluxons.

Recent data[9] on $Bi_2Sr_2CaCu_2O_{8-y}$ has shown that the onset of superconductivity is characterized by two transition temperatures. The upper transition at T_c^c=86.4 K corresponds to transport properties normal to the CuO_2 layers, i.e. a drop in the resistivity and the onset of a nonlinear I-V relation or a critical current. The lower transition at T_c^{ab}=84.3 K corresponds to transport properties parallel to the CuO_2 layers, i.e. vanishing of the resistivity and onset of a nonlinear I-V relation. I propose that the observed T_c^c corresponds to the fluxon transition.

2. Vortex and Fluxon Transitions

The free energy of a layered superconductor can be solved in two limits[10]. First, when the Josephson coupling J between layers vanishes there is a vortex (Kosterlitz-Thouless) phase transition at $T_v=\tau/8$; at $T>T_v$ the mean vortex separation is in terms of the coherence length ξ_0 and the vortex core energy E_c,

$$\xi_v = \xi_0 \exp[-E_c/(2T-\tau/4)]. \tag{1}$$

Second, in the limit $E_c\to\infty$ while $J\neq 0$, the fluctuations of fluxon loops decouple the layers above a fluxon phase transition at $T_f=\tau$. At $T<T_f$ the scale of the fluctuating loops is the fluxon correlation length

$$\xi_f = \xi_0 (T/J)^{1/(2-2T/\tau)} . \tag{2}$$

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To solve the full 3-dimensional (3D) problem with both vortices and fluxons I proceed by comparing the correlation lengths ξ_v and ξ_f. If $\xi_f<\xi_v$, J is renormalized to strong coupling on a scale shorter than ξ_v and vortices are not available to interfere with the fluxon scaling. A strong J implies an isotropic system, so that $\xi_f<\xi_v$ is a sufficient condition for a 3D ordered phase. On the other hand, if $\xi_v<\xi_f$, vortices on a scale r interfere in the renormalization of J and the system remains anisotropic with vortex fluctuations, i.e. it is disordered. Hence the criterion for T_c is $\xi_v\approx\xi_f$ and from Eqs. (1,2)

$$T_c \approx \tau\frac{E_c+(\tau/8)\ln T_c/J}{E_c+\tau\ln T_c/J} \tag{3}$$

This shows that T_c is close to the fluxon transition $T_c\approx\tau$ for J which is not exponentially small, i.e. $J/T_c>\exp(-E_c/T_c)$. For $E_c/\tau \gtrsim 1$ T_c as function of J can vary by much more then the XY value of 2.4 and therefore account for the experimental data on superlattices. Similar conclusions apply using second order renormalization group[10].

3. Fluxon transition in $Bi_2Sr_2CaCu_2O_{8-y}$

I propose that the experimentally observed T_c^c corresponds to the fluxon transition, which for a finite E_c is not a strict phase transition, but rather a sharp crossover transition. For $T_c<T<T_f$, J renormalizes up to the scale ξ_v as

$$J^R \approx J(\xi_v/\xi_0)^{2(1-T/\tau)} \tag{4}$$

A given layer with area L^2 has then L^2/ξ_v^2 segments, each with Josephson coupling J^R. Since different segments are uncorrelated, the sum of currents involves $(L^2/x_v^2)^{1/2}$, i.e.

$$I_c \sim J^R\frac{L}{\xi_v} \approx J\frac{L}{\xi_0}\exp[\frac{E_c}{2\tau}\frac{1-2T/\tau}{T/\tau-1/8}] \quad . \tag{8}$$

For small vortex fugacity, $\exp(-E_c/\tau)\lesssim 1$, I_c has a sharp crossover at $T\approx\tau/2$, reflecting the fluxon transition of uncorrelated segments at $T\approx\tau$; this crossover therefore identifies the transition at T_c^c. Note that the current density $I_c/L^2\to 0$ for large L, i.e. the system exhibits only short range ($\sim\xi_v$) order; long range order sets in at T_c which should correspond to T_c^{ab}.

4.Conclusions

I have shown that the allowed range of T_c as anisotropy is varied can be much larger than the XY value of the XY model. The distinction between a layered superconductors and an XY model is the presence of a core energy for point vortices which is an additional form of anisotropy. For a large core energy T_c approaches the upper limit of the fluxon transition.

The fluxon transition itself accounts for the curious phenomenon[9] of Josephson supercurrents flowing between resistive 2D layers. Thus at T_c^c J starts to renormalize to stroger values though a full 3D order is not yet achieved.

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