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Threshold electric field in unconventional density waves

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As it is well known most charge-density waves (CDW's) and spin-density waves exhibit nonlinear transport with well-defined threshold electric field E_T. Here we study theoretically the threshold electric field of unconventional density waves. We find that the threshold field increases monotonically with temperature without divergent behavior at T_c, unlike the one in conventional CDW. The present result in the three-dimensional weak pinning limit appears to describe rather well the threshold electric field observed recently in the low-temperature phase of α-(BEDT-TTF)$_2$KHg(SCN)$_4$.

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I. INTRODUCTION

A striking feature of superconductors discovered after 1979 is that they are mostly unconventional.[1] The case of *d*-wave superconductors for both the hole-doped and electron-doped high-T_c cuprates is now well established.[2–5] Also most heavy fermion superconductors and organic superconductors appear to be unconventional.[6–9]

Therefore it is very natural to consider unconventional density waves (UDW) within this general context. In conventional density waves the order parameter $\Delta(\mathbf{k}) \propto \langle \psi^+_{\mathbf{k},\sigma}\psi_{\mathbf{k}-\mathbf{Q},\sigma}\rangle$ is independent of $\mathbf{k}$. In UDW $\Delta(\mathbf{k})$ is no longer constant, but $\propto \cos(bk_y)$ for example. Recently a model of unconventional SDW was proposed and its thermodynamics and optical properties were studied.[10,11]

The object of this work is to study the threshold electric field of UCDW and USDW associated with the Fröhlich conduction of UDW. This is motivated by the threshold electric field E_T measured in the low-temperature phase (LTP) of α-(BEDT-TTF)$_2$KHg(SCN)$_4$,[12] where the LTP appears not to be conventional DW. There is no x-ray or NMR signature characteristic to the conventional charge-density wave (CDW) or spin-density wave (SDW). E_T in this salt increases monotonically with increasing temperature somewhat similar to the one observed in SDW of Bechgaard salts (TMTSF)$_2$PF$_6$.[13–15] However the details are quite different. At low temperature the observed E_T increases linearly with T. Also the enhancement at T_c is much larger than the one observed in SDW of Bechgaard salts. The nature of the LTP of α-(ET)$_2$KHg(SCN)$_4$ is not well understood despite many studies on the magnetoresistance, the Schubnikov–de Haas effect, and the Haas–van Alphen effect.[16] Roughly speaking α-(ET)$_2$ salts may be put into two groups: one superconducting and another with this mysterious LTP.

It appears that α-(ET)$_2$MHg(SCN)$_4$ with $M=$K, Tl, and Rb belong to the group with the LTP. At least the sensitivity of the LTP to magnetic field indicates that the LTP is not a SDW but a kind of CDW.[17,18] Indeed the H-T phase diagram of the LTP in α-(ET)$_2$KHg(SCN)$_4$ determined by magnetoresistance measurement is very similar to the one of Fulde-Ferrell-Larkin-Ovchinikov (FFLO) state[19,20] in a *d*-wave superconductor.[21] The FFLO in a d-wave superconductor extends to much higher magnetic field than the one in *s*-wave superconductors.[19,20]

If we assume that the Pauli paramagnetism is driving the magnetic phase transition, the H-T phase diagram of UCDW is the same as the one in a *d*-wave superconductor. Also we shall see later that E_T in UCDW describes well the threshold electric field observed in the LTP of α-(ET)$_2$KHg(SCN)$_4$. Therefore we may conclude that the LTP of some of the α-(ET)$_2$ salts is UCDW.

II. PHASE HAMILTONIAN AND THE THRESHOLD ELECTRIC FIELD

In terms of the phase $\Phi(\mathbf{r},t)$ of DW the phase Hamiltonian[22,23] is given for finite temperature by[13,14]

$$H(\Phi)=\int d^3r\left\{\frac{1}{4}N_0 f\left[v_F^2\left(\frac{\partial\Phi}{\partial x}\right)^2+v_b^2\left(\frac{\partial\Phi}{\partial y}\right)^2+v_c^2\left(\frac{\partial\Phi}{\partial z}\right)^2+\left(\frac{\partial\Phi}{\partial t}\right)^2-4v_F eE\Phi\right]+V_{imp}(\Phi)\right\}, \tag{1}$$

where N_0 is the density of states in the normal state at the Fermi surface per spin, $f=\rho_s(T)/\rho_s(0)$, where $\rho_s(T)$ is the condensate density and E is an electric field applied in the x direction. Here v_F, v_b and v_c are the characteristic velocities of the quasi-one-dimensional electron system in the three spatial directions. For UDW the condensate density is the same as the superfluid density in *d*-wave superconductors.[24]

Now let us consider $V_{imp}(\Phi)$, the pinning potential due to impurities. It is immediately clear that if we consider point-like scatterers (s wave), the potential would be zero at every

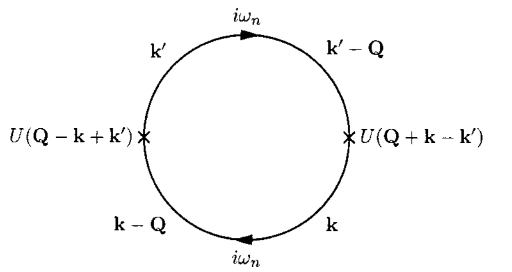

FIG. 1. The diagram of the lowest-order contribution of impurities to the pinning potential is shown. The solid line denotes the electrons, the crosses denote the impurities.

order in the impurity scattering due to the zero average of the gap. Beyond this approximation, one can take other wave-vector-dependent terms into account, originated from an expansion in terms of Fermi surface harmonics, which are plane waves in our quasi-one-dimensional orthorhombic system. Indeed such a model has been introduced by Haran and Nagi[25] in order to describe the defects introduced in high-T_c cuprates by electron irradiation. In fact this model is successfully applied to formulate the upper critical field of the electron-irradiated YBCO.[26–28]

The form of the important matrix element (with the wave vector close to the nesting vector) reads as

$$U(\mathbf{Q}+\mathbf{q})=V_0+\sum_{i=y,z} V_i \cos(q_i\delta_i), \tag{2}$$

where the higher harmonics are neglected because of their smaller coefficient. The first-order term in the pinning potential vanishes because of the wave-vector dependence of the gap in UCDW, while in USDW it vanishes already due to the sum over spins. In the following we assume that the gap of UCDW is given by $\Delta(\mathbf{k})=\Delta\cos(k_y b)$. Note that we can obtain identical results with $\Delta(\mathbf{k})=\Delta\sin(k_y b)$ and for a gap dependent on k_z as well.

The lowest order nonvanishing diagram contains a closed loop with two crosses of impurities (see Fig. 1), and the pinning potential is obtained as

$$V_{imp}(\Phi)=-\frac{8V_0V_yN_0^2}{\pi}\sum_j \cos\{2[\mathbf{Q}\mathbf{R}_j+\Phi(\mathbf{R}_j)]\}\Delta(T)\times\int_0^1\tanh\frac{\beta\Delta(T)x}{2}E(\sqrt{1-x^2})\times[K(x)-E(x)]dx, \tag{3}$$

where $\Delta(T)$ is the temperature-dependent order parameter,[11,24] $\mathbf{R}_j$ is an impurity site, $K(z)$ and $E(z)$ are the complete elliptic integrals of the first and second kind, respectively. Note Eq. (3) is similar to the one for SDW (Refs. 13 and 14) except for the x integral coming from the $\mathbf{k}$ dependence of the gap. Then following FLR,[22,23] in the strong pinning limit the threshold electric field at $T=0$ K is given by

$$E_T^S(0)=\frac{2k_F}{e}\frac{n_i}{n}N_0^2V_0V_y\frac{16}{\pi}0.5925\Delta(0), \tag{4}$$

and for general temperature it is obtained as

$$\frac{E_T^S(T)}{E_T^S(0)}=\frac{\rho_s}{\rho_s(T)}\frac{\Delta(T)}{\Delta(0)}\frac{1}{0.5925}\int_0^1\tanh\frac{\beta\Delta(T)x}{2}\times E(\sqrt{1-x^2})[K(x)-E(x)]dx. \tag{5}$$

At low temperature E_T^S increases linearly with T since $\rho_s(T)$ is linear in this range:

$$\frac{E_T^S(T)}{E_T^S(0)}=1+2\ln 2\frac{T}{\Delta(0)}, \tag{6}$$

and the other quantities change like T^3. At T_c, Eq. (5) gives

$$\frac{E_T^S(T_c)}{E_T^S(0)}=\frac{\pi^3}{7\zeta(3)}\left(\frac{2\pi}{\sqrt{e}\gamma}\right)^{-1}\frac{2\pi^2}{32\times 0.5925}\approx 1.793, \tag{7}$$

where $\gamma=1.781$. Close to the transition temperature E_T increases linearly:

$$\frac{E_T^S(T)}{E_T^S(0)}=\frac{E_T^S(T_c)}{E_T^S(0)}\left[1-0.42\left(1-\frac{T}{T_c}\right)\right]. \tag{8}$$

With its $T=0$ K slope, the normalized threshold field would reach 1.64 at T_c, so it is almost linear in the strong pinning limit.

The strong pinning limit implies that the pinning potential is so strong that one single impurity is adequate to pin the UCDW. The applicability of this concept has been questioned recently.[29] On the other hand, unless impurities are introduced by x-ray irradiation or by some violent means,

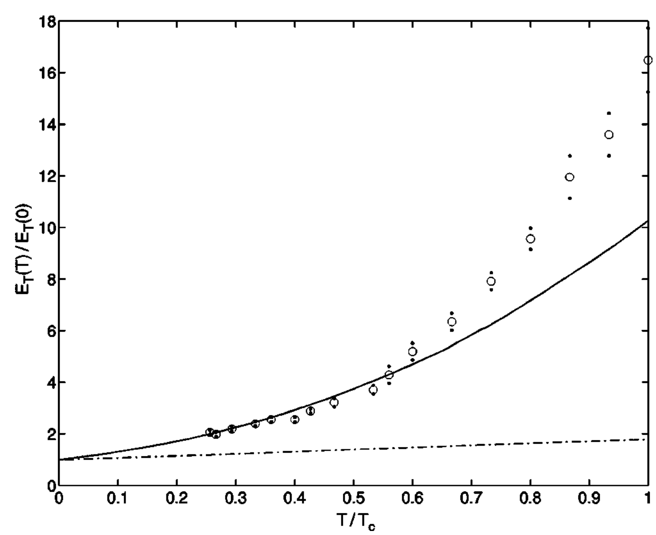

FIG. 2. The normalized threshold field plotted as a function of the reduced temperature in the strong pinning (dashed-dotted line), and weak-pinning (solid line) limit. The circles are the measured values in α-$(ET)_2KHg(SCN)_4$, the points are the error bars.

the weak-pinning limit appears to prevail.[15] Then for the 3D weak-pinning limit we obtain[22,23]

$$\frac{E_T^W(T)}{E_T^W(0)} = \left(\frac{E_T^S(T)}{E_T^S(0)} \right)^4. \tag{9}$$

The threshold field is shown in Fig. 2 together with the data taken from Ref. 12. We see that the 3D weak-pinning limit is qualitatively consistent with the experimental data. (The fitting was made by taking into account the much smaller experimental error at lower temperatures.) In other words, unconventional CDW appears to describe the LTP of α-$(ET)_2KHg(SCN)_4$. Also the present result applies also for unconventional SDW. On the other hand there is an obvious discrepancy as T approaches T_c. Coulomb hardening [not included in Eq. (1)] is an unlikely source of this discrepancy due to ample screening by other bands in α-$(ET)_2$ unaffected by the DW transition. In a forthcoming paper, we shall discuss the effect of imperfect nesting in order to improve the agreement between experiment and theory due to the fact that the α-$(ET)_2$ salts' Fermi surface contains two dimensional parts as well.

III. CONCLUDING REMARKS

Within the theoretical framework developed in Ref. 11 we study the threshold electric field of unconventional CDW. The present result for the 3D weak-pinning limit appears to describe the data taken from the LTP of α-$(ET)_2KHg(SCN)_4$ satisfactorily. For this we need impurities with anisotropic scattering amplitude.[25,30] Together with the H-T phase diagram which is very parallel to the FFLO state in UCDW, the present result indicates strongly that the LTP of α-$(ET)_2MHg(SCN)_4$ with $M=$K, Tl, and RB is of unconventional CDW. In this respect a further study of the threshold electric field in the presence of magnetic field will be of great interest.

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