Intrinsic Inhomogeneity in strongly correlated systems: a possible playground for the cosmology in the lab

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Abstract. “Intrinsic inhomogeneity” by competing orders has attracted a keen interest in recent studies of strongly correlated systems. The superconducting gap is inhomogeneous at a nano-scale in high-temperature superconductors, the auto correlation function of which quite resembles that of the galaxy distribution. We have studied transport properties in strongly correlated systems, and have found a novel inhomogeneous state in a charge-ordered organic conductor. This particular material could be a good playground for self-gravitating systems, because (i) the Coulomb interaction is unscreened and thus long-ranged in the charge-ordered state. (ii) The system is close to the quantum critical point, where all the physical properties are scale invariant. (iii) The charge ordered domain accompanies lattice strain which works as a long-range attractive force.

1. Introduction
Strongly correlated (electron) systems are a system that the electron-electron interaction is strong enough to have a one-electron picture invalid. They have been one of the central research fields in condensed-matter physics, because various unpredictable properties and functions emerge from tremendous degrees of freedom spontaneously [1].

Intrinsic inhomogeneity is a recent hot topic in this field, which is a kind of self-organization phenomena of conduction electrons. A prime example is the high-temperature superconductivity in copper oxides, in which nano-scale phase-separation of superconducting domains is observed in scanning-tunnel-microscope experiments [2]. Such a self-organization arises not from disorder, but from the electron-electron interaction, hence the name “intrinsic inhomogeneity” [3].

As is generally agreed, our understanding of the early universe is far from satisfactory. Perhaps this is due to lack of experimental tests for proposed theories. Since the evolution of the early universe is a kind of phase transition/crossover, various phase transitions in condensed matter could be a test station. Such studies have been called “cosmology in the lab” [4], where liquid crystals, superfluid He³, high-temperature superconductors, and Josephson junctions were examined. Here we will propose a certain organic conductor could be a new candidate for the playground for the cosmology.

2. Inhomogeneity from competing orders
Although the mechanism of the high-temperature superconductivity in copper oxides is not yet understood, there appears increasing evidence that various orders compete and coexist close to the superconducting phase. As a result, superconducting nano-domains are inhomogeneously distributed
in a single crystal of high-temperature superconductors, where they form a percolation network in the background insulating phase called the pseudogap phase [2].

Figure 1 shows auto correlation functions of two different systems. The one is that of the superconducting-domain distribution in the high-temperature superconductors [5], and the other is that of the galaxy distribution [6]. One can find that gross features of the two are similar, which inspires us to look for some common physics flowing underneath. In fact, the former system shares common features to self-gravitating systems. The effective interaction between the superconducting nano-domains is attractive (and hopefully long-ranged) [7], and all the physical parameters are scale-invariant owing to the quantum critical point [1]. Thus we propose inhomogeneous states from competing orders as a new test station for the large-structure formation in the galaxy.

3. Charge inhomogeneity in an organic conductor
In addition to the three features (attractive, long-ranged and scale-invariant), nonequilibrium states are essential to the universe. Since the inhomogeneous superconducting nano-domains are at a thermal equilibrium, a more suitable system is desired. We have found that the organic conductor $\theta$-(BEDT-TTF)$_2$CsM(SCN)$_4$ (M=Zn and Co) is a promising candidate having inhomogeneity and nonequilibrium natures simultaneously [8, 9].

As shown in Fig. 2(a), two diffuse peaks are observed in the x-ray diffraction of a single crystal of $\theta$-(BEDT-TTF)$_2$CsM(SCN)$_4$ at 20 K, which correspond to charge-ordered domains with different modulations denoted by $q_1=2/3b_1+ib_2+1/3b_3$ and $q_2=1/2b_3$ ($b_i$ is the reciprocal lattice vector for the corresponding primitive lattice vector $a_i$) [10]. The charge order is an order of conduction electrons in which the electrons are regularly aligned on lattice sites through the off-site Coulomb repulsion like the Wigner crystal. In the charge order with the $q_1$ modulation, for example, the electrons are aligned at every two site along the $b_3$ axis, as schematically drawn in the inset of Figure 2. Importantly, the $q_1$ and $q_2$ peaks are very broad and weak, implying short-range orders with a typical length scale of 10 nm. In other words, the two kinds of charge-ordered domains modulated by $q_1$ and $q_2$ coexist to form an “intrinsically inhomogeneous” state at nano scale.

Similarly to the high-temperature superconductors, this inhomogeneous state includes common features to self-gravitating systems. First, the transition temperature of the charge ordering is suppressed down to 4 K, suggesting that the system is close to the quantum critical point, where all the
quantities are expected to be scale-invariant. Second, because of the insulating nature of the charge-ordered state, the Coulomb interaction is unscreened and long-ranged. Third, the charge-ordered domain strongly couples with lattice distortion (strain field), through which the effective interaction between the charge-ordered domains with the same $q_i$ is expected to be attractive. Most importantly, we can control the competition of the charge ordered domains by external current. In Fig. 2(b), the $q_2$ peak systematically loses its intensity with increasing current, whereas the $q_1$ peak remains intact (not shown here) [8]. This is an essentially nonequilibrium state of the competing charge-orders, which has never been reported before.

Figure 2 (a) X-ray diffraction of a single crystal of the organic conductor $\theta$-(BEDT-TTF)$_2$CsM(SCN)$_4$ at 20 K [10]. The data were scanned along the $b$ direction. The two peaks $q_1$ and $q_2$ indicate two different charge-ordered domains. The inset shows the charge order pattern denoted by $q_L$. (b) The $q_1$ peak in external currents. The peak substantially decreases with current, indicating the melting of the charge-ordered domain by the external current [8].

Figure 3 Giant nonlinear conduction in $\theta$-(BEDT-TTF)$_2$CsM(SCN)$_4$ plotted as a function of external current for various temperatures.

It is very common in condensed-matter physics to control the excited states. We can apply various impetuses such as current, electric/magnetic field, electromagnetic wave (light), temperature gradient, pressure etc., and can measure how the system responds to them. Thus, no matter how similar the two
distributions/patterns may look, we can often distinguish them by the response to impetuses. In the present organic conductor, the current-induced change in the $q_2$ peak results in the giant nonlinear conduction in the current-voltage characteristics. Figure 3 shows the nonlinear resistance of $\theta$-(BEDT-TTF)$_2$CsM(SCN)$_4$, where the resistance changes with temperature and current. Regard that the charge-ordered state as an ice of electrons, and the electrical current as a flow of electrons. On a wintry cold day, water on a pond is frozen, but water on a river continues to flow. The data in Figure 3 could be an analogue to this. The resistance of the sample reflects the degree of melting, where it decreases by increasing either temperature or external current.

If a theory suggested for the galaxy formation could calculate the excited state to a particular perturbation (although it is impossible to excite the universe), it would be examined in the corresponding condensed-matter system. Theories in condensed-matter physics have been established in this way, which is indeed a strong advantage in this field.

Another thing we have to remember is that unexpected properties can emerge in real systems, which cannot be predicted from numerical simulations at small scale. A large variety of properties and functions in solids basically come only from the “well-understood” Coulomb force, the most unexpected one of which is the high-temperature superconductivity. In the same way, the gravity may have already given various properties in the galaxy, which are still unknown to us at present. A quantitative comparison with inhomogeneous states in solids may shed light on unexpected nature of self-gravitating systems.

4. Summary

In this paper we have proposed the competing charge order in the organic salt $\theta$-(BEDT-TTF)$_2$CsM(SCN)$_4$ could be a promising candidate for a test station of the galaxy distribution. It includes some important features (long-ranged, attractive, scale-invariant and nonequilibrium) common to the self-gravitating systems.

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