Quantum Melting of Charge and Spin Orders

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Regular alignments of charge and/or spin densities of electrons are universally observable phenomena in electronic systems. These include antiferromagnetic (spiral) orders, charge (spin) density waves, and charge orders including stripes. A common feature in these phenomena is spontaneous breaking of the translational symmetry, where the periodicity formation is in many cases ascribed to electron correlation effects. In particular, the periodic alignment of charge and spin becomes remarkably stable if the electron concentration satisfies "commensurability condition", where the electron filling, n is a simple fractional number or integer. Mott insulator is the most conspicuous example of such commensurate insulators, where the filling is an odd integer. Many other examples are found in charge orders of transition metal compounds and organic systems, where the filling is a simple fractional number such as 1/2 and 2/3. Various dramatic open phenomena such as cuprate high-Tc superconductivity and colossal magneto-resistance in manganites are observed under proximity of such commensurate orders. To clarify such dramatic phenomena, elucidating mechanisms of commensurate insulator formation and its quantum melting are required.

We have studied physics of quantum melting transitions of charge and spins. It has turned out that these transitions can indeed be described only when taking account full quantum mechanical fluctuations beyond the mean-field level. For this purpose, we have developed new numerical as well as analytical tools, since the available tools have various types of difficulties in attacking them. The minus sign problem is a typical difficulty, because of which, for example, most numerical methods are not feasible for geometrically frustrated systems. Frustration effects have crucial importance in quantum meltings. We have developed path-integral renormalization group (PIRG) method for numerical calculations [1,2] and the correlator projection method [3,4] for analytic treatments to overcome the difficulties. In PIRG calculations, metal-insulator transitions, magnetic transitions and other possibilities of transitions are carefully examined with finite size scalings. With the newly developed tools, we have obtained the following remarkable insight.

(1) For lattice models with the long-range Coulomb interaction, the charge order is indeed stabilized as insulators only at commensurate fillings with some simple fractions such as 1, 1/2, 1/3, 2/3…, while quantum fluctuations destroy the ordering at other fillings ending up with metals[5]. For example, at n=1/4, the charge order is stable at two-orders of magnitude larger electron density than the quantum melting point of the Wigner crystal in a 2D electron system in the continuum space (Figure 1). Though the band theory predicts a simple distinction between metals and insulators, the simple metal a la the band theory actually has a rich hierarchy with many commensurate insulator phases contained.

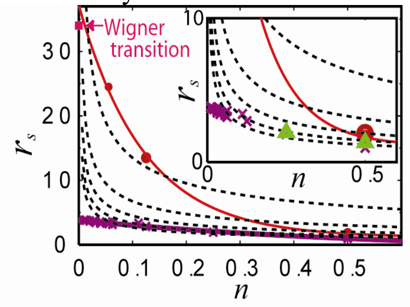

Fig.1: Solid-liquid phase boundary in plane of the filling n=1/l with integer l vs. electron gas parameter r_s. PIRG results with red circles for spin-1/2 (open) and spinless (filled) fermions are compared with Hartree-Fock results (purple crosses (spinless) and green triangles (spin-1/2). The red solid curves are guides for the eye. The inset is enlarged illustration.

(2) Spin orders in commensurate charge-ordered phase melts when the geometrical frustration gets large [6,7]. Quantum spin liquid phase then appears in Mott insulator near the metal-insulator transition and sandwiched by the metal and antiferromagnetic insulator phases (Fig.2). In this spin liquid insulator phase, none of translational symmetry breakings such as (staggered) flux state are stabilized and the spin excitation is gapless [8].

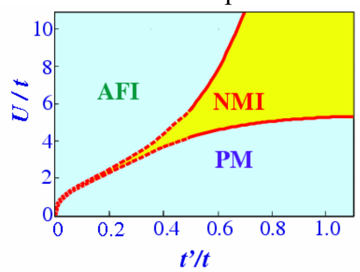

Fig.2: Phase diagram obtained by PIRG for the Hubbard model at half filling in the plane of the onsite Coulomb interaction scaled by the electron transfer U/t and the frustration parameter t'/t for anisotropic triangular lattice with notations of paramagnetic metal (PM), nonmagnetic insulator (spin liquid) (NMI) and antiferromagnetic insulator (AFI).

(3) When the metal-insulator transition is the first-order type at zero temperature, it accompanies a first-order boundary line at finite temperature ending at a second-order critical point at a nonzero temperature. When this critical temperature is suppressed to zero, marginally quantum critical point appears [9-11]. This marginal quantum critical point does not follow Ginzburg-Landau-Wilson scheme and does belong to a new type of universality class. Unusual critical exponents for this quantum phase transition are obtained and they agree with recent careful experiments. It has been shown that critical density fluctuations characterizing this Mott criticality generates non-Fermi-liquid character in the metallic side with a novel mechanism of superconductivity.

References

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