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Pomeranchuk effect in twisted bilayer graphene

1. **Isospin Pomeranchuk effect and the entropy of collective excitations in twisted bilayer graphene**
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   arXiv:2008.10830

2. **Entropic evidence for a Pomeranchuk effect in magic angle graphene**
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   arXiv:2009.01836

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The phase diagram of twisted bilayer graphene keeps bringing up surprises. After the unexpected observation of a succession of broken symmetry phases at integer and non integer band fillings[1, 2], (the "cascade" of phase transitions, see also[3, 4, 5]) a new intriguing phase has been identified at finite magnetic fields and/or at finite temperatures[6, 7].

The transition to this new phase has been associated to the Pomeranchuk effect, because it is accompanied by a large change in entropy (see below). In 1950 I. Pomeranchuk suggested[8], on theoretical grounds, that ^{3}He could solidify upon increasing temperature, as the nuclear spins fluctuate more freely in the solid phase. The resulting increase in entropy more than compensates the entropy loss due to the localization of the atoms at the nodes of the lattice. This prediction was later confirmed, and it lead to a successful technique[9] for cooling liquid ^{3}He. When a mixture of solid and liquid ^{3}He is compressed adiabatically, part of the liquid is converted to a solid. The newly formed solid has the same entropy as the liquid that it replaces, so that its temperature goes down. Counter intuitive transitions driven solely by changes in entropy occur in hard core models. Special shapes favor high entropy phases with directional order over disordered phases with lower translational entropy[10]. An electronic transition which involves a large change in entropy, due to the formation of free spins, is the metal insulator transition[11] in V_2O_3.

The transition observed in[6] takes place when the carrier density in twisted bilayer graphene is near between one and two holes per moiré unit cell (in the conventional notation, $-2 \lesssim \nu \lesssim -1$). The conductivity of a sample with a twist angle $\theta \approx 1.12°$, near the first

magic angle, is measured as function of temperature and magnetic field. The conductivity at zero magnetic field and temperatures of 400 mK or below shows a metallic behavior for this range of fillings (it also shows evidence of broken symmetry phases near other integer fillings). As the magnetic field is increased, $B \gtrsim 6$T, a minimum in the conductivity develops, suggesting the existence of a new (metallic) phase at finite fields. The appearance of new features for $-2 \lesssim \nu \lesssim -1$ is further confirmed by measurements of the Hall density. Tentatively, ref.[6] identifies the field induced phase with the counterpart of the broken symmetry phases observed at $\nu = -3$ and $\nu = -2$ at zero field.

The authors of ref.[6] also analyzed the dependence on temperature of the transport properties in the absence of a magnetic field. Remarkably, features similar to those found at finite magnetic fields appeared at finite temperatures, $T \gtrsim 5$ K, also for $-2 \lesssim \nu \lesssim -1$.

The paper then compares the magnetic field, B^*, at which the new phase appears at zero temperature, the temperature, T^*, at which it appears at zero field, and the expected magnetization, m^*_ν, in the cascade model, and obtains an estimate of the entropy of the phase, $s \approx (g\mu_B m^*_{\nu\approx -1} B^*)/T^*$. This analysis gives $s \sim k_B$, consistent with one free spin per moiré unit cell.

Finally, ref.[6] reports measurements of the temperature and magnetic field dependence of the chemical potential, using the setup described in[12]. These measurements allow the determination of the entropy (see below). The values obtained are consistent with an increase in the entropy between $\nu = 0$ and $\nu = 1$ of $\Delta s \approx 1 \times k_B$. There is no abrupt change in the entropy as function of filling or temperature, which seems to rule out a sharp first order transition.

Ref.[7] extracts the entropy, and other thermodynamic quantities, from measurements of the electronic compressibility, κ, as function of density of carriers, n, temperature, T, and magnetic field, B. The derivatives of the free energy, Ω, with respect to the parameters $\{n, T, B\}$ give the quantities $\{\mu, s, m\}$, that is, the chemical potential, entropy, and magnetization. Finally, n and μ are related to the compressibility, $\partial\mu/\partial n = \kappa^{-1}$. Successive integrations of $\kappa^{-1}(n, T, B)$ with respect to $\{n, T, B\}$ allow the authors of ref.[7] to extract the chemical potential, entropy, and magnetization of the system.

The electronic compressibility is measured in[7] in two independent ways. A local probe, consisting of a very sensitive single electron transistor is used to scan a twisted bilayer graphene: this transistor measures variations of the chemical potential in the twisted graphene bilayer, which are induced by a small modulation of the back gate. A global measurement is also performed, by bringing near the twisted bilayer a clean graphene monolayer. The densities in the two systems are controlled by a top and a bottom gate. When the charge density in one of the systems is kept constant and the other is changed, the varations in the potential of the gate which controls the changes give the dependence of the chemical potential on the varying charge density. This technique was already applied to twisted bilayer graphene in[5].

The local and extended compressibility measurements reported in[7], although performed on different samples, give quite consistent results. In both cases, evidence of an anomalous behavior near $\nu = 1$ at finite temperatures is found. The sharp jump in the inverse compressibility most likely is a proxy for the underlying first order phase transition. The associated change in entropy, $s \approx k_B$, is consistent with the existence of independently fluctuating

spins. Finally, Ref.[7] uses the positions of the jumps in the compressibility to define a phase boundary in the $\{n, T, B\}$ parameter space. This boundary separates two phases with metallic conductance but significantly different entropy.

It is worth noting that there is a class of strongly correlated systems which show phases with different magnetic orderings, first order phase transitions and phase coexistence, and very large changes in the transport properties at the transitions. These are the double exchange systems[13], or colossal magnetoresistence (CMR) compounds[14]. In these systems, pre-existing magnetic moments are strongly coupled to the spins of the electrons at the Fermi energy, leading to a strong correlation between magnetic order and transport properties (and to large changes in entropy). It would be interesting if the narrow bands of twisted bilayer graphene could lead to local magnetic moments and to itinerant electrons simultaneously.

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