DOI:10.36471/JCCM_December_2022_02

A gate-tunable moiré Kondo lattice

Gate-tunable heavy fermions in a moiré Kondo lattice
Authors: Wenjin Zhao, Bowen Shen, Zui Tao, Zhongdong Han, Kaifei Kang, Kenji Watanabe, Takashi Taniguchi, Kin Fai Mak, Jie Shan

https://arxiv.org/abs/2211.00263

Recommended with a Commentary by T. Senthil, Massachusetts Institute of Technology

In the last few years, a number of fascinating many body phenomena have been discovered in the so-called moire materials. These are two dimensional materials where the interference between two slightly different crystalline arrangements leads to a long period moire pattern (a ``superlattice") on which the electrons move. The classic example is two layers of graphene with a relative twist near a magic angle of about 1.1 deg: this misalignment produces the moire pattern. Near the magic angle, the electronic bands near the chemical potential become very narrow and the effects of electron-electron interaction get enhanced. Since the initial report of interaction-driven insulators[1] and proximate superconductivity[2] in twisted bilayer graphene, a number of other such moire materials have been explored [3]. The realization of strong correlation physics in these two dimensional materials provides an opportunity to study them in a highly tunable experimental platform. Indeed the charge density, the bandwidth, and (in some cases) the band topology can all be controlled with electrical gates leading to a fascinating slew of phenomena. There is hope that these moire material platforms can both shed light on long standing mysteries in strong correlation physics while also throwing up new challenges that the field has not had to confront in the past.

The selected paper, from the Cornell group lead by Jie Shan and Kin Fai Mak, presents a realization of a venerable model of strong correlation physics: a system of localized magnetic moments that are coupled together by spin exchange with a separate set of mobile electrons. This is known as a Kondo lattice. It describes a number of rare-earth inter metallic compounds where localized f-orbitals possess magnetic moments which are coupled to a conduction electron sea. The interesting question is the fate of the local moments at low temperature. On the one hand, the coupling to the mobile electrons induces an inter-moment interaction that - in the simplest scenario - promotes magnetic ordering of the local moments. The mobile electrons then form a fermi surface which will be affected (through diffraction by the magnetic lattice) in some straightforward way. On the other hand, there is also the possibility of Kondo screening where-

in the local moments get absorbed into the fermi sea. The resulting non-magnetic metallic state, is described - in the simplest scenario - by Landau's fermi liquid theory, albeit with heavy masses for the low energy quasiparticles (hence the name heavy fermi liquid for this state). Interestingly the size of the fermi surface in the heavy fermi liquid state is correctly given only if one includes both the mobile electrons and the magnetic moments in the Luttinger count. These two possibilities - the paramagnetic heavy fermi liquid metal and the magnetically ordered metal - are both seen in rare earth alloys. Their competition can, in some cases, be tuned and the resulting evolution results in a number of mysterious phenomena including the breakdown of fermi liquid theory, and the emergence of superconductivity.

The highlighted paper studies a moire material made by a sandwich of two different monolayers ($MoTe_2$ and WSe_2) of Transition Metal Dichalcogenides (TMD). Each of these separately forms a honeycomb lattice. The sandwich consists of these two monolayers stacked together in the AB pattern. A slight lattice mismatch produces a moire superlattice (there is no twisting in this system). TMD materials have a strong spin-orbit coupling due to which the spin of the electron is locked to its valley. In the AB arrangement, the natural inter-layer tunneling is between electrons whose spins point in opposite directions in the two valleys: this weakens the tunneling matrix element $t_\perp$. The moire potential is felt more strongly by the $MoTe_2$ layer and its band is narrower than the relevant WSe_2 band. A perpendicular displacement field D tunes the energy separation Δ between the bands of the two layers. (For density functional calculations, see Ref. [4]).

If the displacement field is adjusted so that the valence band of $MoTe_2$ stays below that of WSe_2, then doping into the valence band from neutrality leads, at first, to the holes occupying just the $MoTe_2$ layer. This situation persists till half-filling of the moire-induced valence band ($\nu = 1$) where a previous study[5] by the same Cornell group found a Mott insulator in a range of displacement field D (in addition there is the expected band insulator at hole filling $\nu = 2$). In this Mott insulator, the electrons are localized on the moire spots. In the present paper the authors study the system in a range of (ν , D). For hole-filling $\nu = 1+x$ (with $x > 0$) for a range of D, rather than continuing to occupy the $MoTe_2$ layer - the excess x holes move to the WSe_2 layer. This is because it is cheaper to pay the energy cost $\sim \Delta$ to occupy the WSe_2 layer than it is to pay the cost U of double occupancy in the $MoTe_2$ layer. This generates the players needed for a realization of the Kondo lattice: local moments in the $MoTe_2$ layer, and a mobile set of electrons in the WSe_2 layer. There is a Kondo exchange coupling between these two degrees of freedom which is proportional to $t_\perp^2 \left(\frac{1}{U} + \frac{1}{U - \Delta} \right)$. As Δ is tuned by the displacement field, the strength of the Kondo exchange can be controlled electrically in this system.

The authors provide evidence that at ν = 1+x, a heavy Fermi liquid arises. The resistivity has an AT^2 temperature dependence at low T, with a coefficient A that increases sharply as x is decreased. (In contrast at fillings $\nu = 2 + x$, there is a relatively weak T^2 component in the resistivity that further has little doping dependence). In a usual correlated Fermi liquid, the A coefficient is proportional to the square of the effective mass m*: in the present context where m* is hard to measure directly, the measurement of A serves as a proxy. The Hall coefficient - from which a ``Hall carrier density" n_H can be defined - shows a striking magnetic field dependence. At low fields, $n_H$ is seen to equal 1-x, the value expected of a ``large fermi surface" where the local moments are absorbed into the fermi sea. Beyond a certain critical field, there is a sudden switch, and n_H is seen to equal -x (which corresponds to just counting the excess holes in the WSe_2 layer). This may plausibly be interpreted as a destruction of the Kondo screening by the Zeeman coupling to the magnetic field. Finally the paper also shows a crossover temperature T * (for $\nu = 1 + x$) below which the resistivity falls; this is associated with the onset of Kondo coherence. Both T* and m* can be gate-tuned, and their evolution is roughly in inverse proportion as expected for a Kondo lattice.

The advent of the Kondo lattice in a moire platform, and the opportunities for tuning various relevant energy scales in-situ, offers hope that the afore-mentioned phenomena like the competition between Kondo screening and magnetic exchange can be studied in exquisite detail in the coming years. The highlighted paper was preceded [6,7,8] by a number of theoretical suggestions for other routes to realizing a Kondo lattice in the world of moire materials. (See also Ref. [9] for a theoretical model of the present paper)). Either the present realization or, if implemented, one of these other suggestions, could open a new window into some of the most vexing open theoretical problems (such as, eg, heavy fermion quantum criticality) in quantum many body physics.

References

[1] Yuan Cao et al, Correlated insulator behaviour at half-filling in magic-angle graphene superlattices. Nature, 556(7699):80, 2018.

[2] Yuan Cao et al, Nature, 556(7699):43, 2018.

[3] Andrei, E.Y., Efetov, D.K., Jarillo-Herrero, P. et al. The marvels of moiré materials. Nat Rev Mater 6, 201–206 (2021).

[4] Zhang, Y., Devakul, T. & Fu, L. Spin-textured Chern bands in AB-stacked transition metal dichalcogenide bilayers. Proc. Natl. Acad. Sci. USA 118, e2112673118 (2021).

[5] T. Li et al, Quantum anomalous hall effect from inter- twined moir´e bands, Nature 600, 641 (2021).

[6] Kumar, A., Hu, N. C., Macdonald, A. H. & Potter, A. C. Gate-tunable heavy fermion quantum criticality in a moiré Kondo lattice. Phys. Rev. B 106, L041116 (2022).

[7] Ramires, A. & Lado, J. L. Emulating heavy fermions in twisted trilayer graphene. Phys. Rev. Lett. 127, 026401 (2021).

[8] Dalal, A. & Ruhman, J. Orbitally selective Mott phase in electron-doped twisted transition metal-dichalcogenides: A possible realization of the Kondo lattice model. Phys. Rev. Res. 3, 043173 (2021).

[9] Guerci, D. et al. Chiral Kondo lattice in doped $MoTe_2/WSe_2$ bilayers. arXiv: 2207.06476 (2022).