Gate-Tunable Heavy Fermions in a Moiré Kondo Lattice

CNF Project Number: 2633-18
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Primary Source(s) of Research Funding: DOE, NSF, AFOSR

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Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator System (NPGS), SC4500 Odd/Even-Hour Evaporator, Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, Dicing Saw - DISCO

Abstract:

The Kondo lattice—a matrix of local magnetic moments coupled through spin-exchange interactions to itinerant conduction electrons—is a prototype of strongly correlated quantum matter [1,2]. We realize a synthetic Kondo lattice in AB-stacked $MoTe_2/WSe_2$ moiré bilayers, in which the $MoTe_2$ layer is tuned to a Mott insulating state, supporting a triangular lattice of local moments, and the WSe_2 layer is doped with itinerant conduction carriers. We observe heavy fermions with a large Fermi surface below the Kondo temperature. We also observe the destruction of the heavy fermions with an abrupt decrease in the Fermi surface size and quasi-particle mass under an external magnetic field. We further demonstrate widely and continuously gate-tunable Kondo temperatures through the itinerant carrier density or the Kondo coupling.

Summary of Research:

Common approaches to realizing strong electronic correlations rely on intermetallic compounds that involve heavy elements like lanthanides [1,2]. The use of naturally occurring elements limits the found material's tuneability. Further, these materials typically have a very complex electronic structure, which makes them hard to describe and predict by theory. We demonstrate a model Kondo system created by stacking a pair of monolayer semiconductors to study quantum phenomena ranging from heavy fermions to exotic quantum phase transitions. We use $MoTe_2/WSe_2$ moiré bilayers, in which the $MoTe_2$ layer is tuned to a Mott insulating state, supporting a triangular moiré lattice of local moments, and the WSe_2 layer is doped with itinerant conduction carriers [3,4]. We observe heavy fermions with a large Fermi surface below the Kondo temperature T^* and that the heavy fermions be destructed by an external magnetic field. The Kondo temperature can be tuned widely and continuously via an applied electric voltage. The study opens the possibility of *in situ* access to the phase diagram of the Kondo lattice with exotic quantum criticalities in a single device based on semiconductor moiré materials [5].

Figure 1 shows the schematic and optical image of a device. We fabricated dual-gated $MoTe_2/WSe_2$ devices using a layer-by-layer dry-transfer technique. We deposited 5-nm Pt contacts on hBN by standard electron-beam lithography and evaporation, followed by another step of electron-beam lithography and metallization to form a bilayer of 5-nm Ti and 40-nm Au to connect the thin Pt contacts on hBN to pre-patterned electrodes.

Figure 2 shows the temperature dependence of the resistance R_{xx} when the device is tuned to a Kondo lattice phase. There is a characteristic temperature T^*, below which resistance drops significantly, and T^* increases with the hole density in the WSe2 layer (ν_W). The inset shows the T^2-dependence of R_{xx} at low temperatures, which is a characteristic of a Landau Fermi liquid. We fit the dependence using $R_{xx} = R_0 + AT^2$, where R_0 is the residual resistance, and $A^{1/2}$ is linearly proportional to the quasiparticle mass. The value is more than an order of magnitude larger than in the region without the formation of the Kondo lattice in the same device. The large enhancement points to the emergence of heavy fermions.

Figure 3 shows the magnetic-field dependence of the Hall density, $\nu^* = B/(eR_{xy}n_M)$ for $\nu_W = 0.35$. We obtain $\nu^* \approx -\nu_W$ for $\nu_{Mo} = 2$, where the Kondo lattice is not formed. For $\nu_{Mo} = 1$, below critical magnetic field (B_c) we obtain $\nu^* \approx 1-\nu_W$. It indicates a hole Fermi surface with density of $1 + \nu_W$.

This result shows that the local moments in the $MoTe_2$ layer are hybridized with the conduction holes in the WSe_2 layer to form a large hole Fermi surface. The observed large Fermi surface, in combination with the

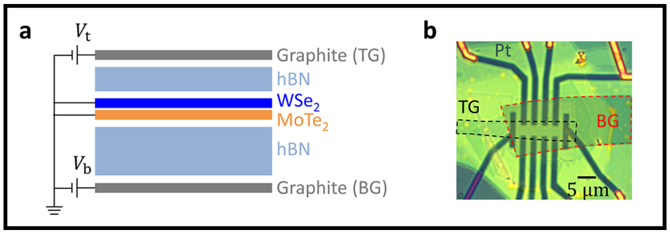

Figure 1: a, Device schematics. b, Optical microscope image of a dual-gated device. The scale bar is 5 µm.

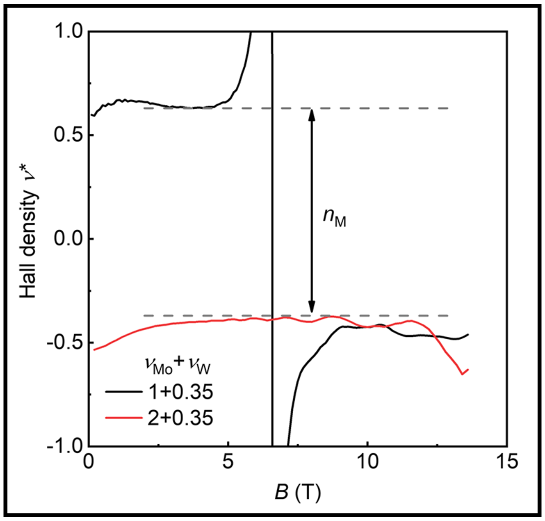

Figure 3: The corresponding magnetic-field dependence of the Hall density ν^* for $\nu = 1 + 0.35$ and $\nu = 2 + 0.35$. A density jump equaling the moiré density n_M occurs around 6 T.

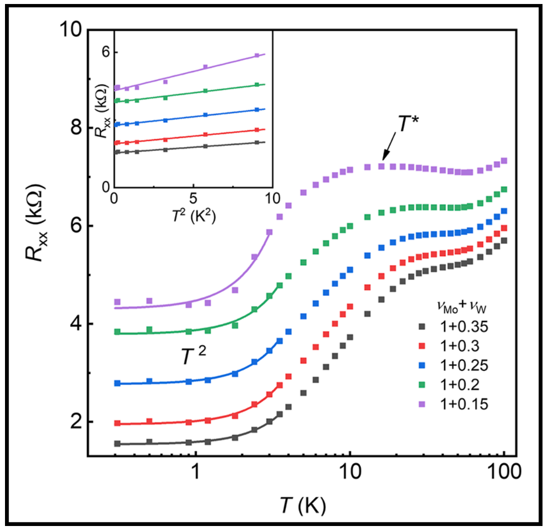

Figure 2: Temperature dependent longitudinal resistance R_{xx} at varying doping densities for $\nu = 1+ \nu_W$. The solid lines are the best fits to the quadratic temperature dependence at low temperatures. The arrows mark the Kondo temperature T^*. The insets show the scaling of R_{xx} with T^2.

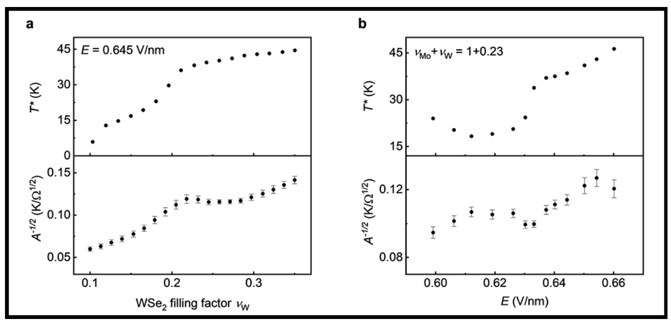

Figure 4: a, Extracted doping dependence of T^* (top) and $A^{-1/2}$ (bottom) at a fixed electric field (E=0.645 V/nm) for $\nu = 1 + \nu_W$. The two quantities show similar dependences. b, Extracted electric-field dependence of T^* (top) and $A^{-1/2}$ (bottom) at a fixed filling factor (ν=1+0.23).

quasiparticle mass enhancement, supports the realization of the Kondo lattice. The Hall measurement also shows that the large Fermi surface with hole density $1 + \nu_W$ is reduced to a small Fermi surface with hole density ν_W when a magnetic field above B_c is applied.

Figure 4 shows the tunability of the Kondo temperature T^* and the parameter $A^{-1/2}$. We show one cut along $E = 0.645$ V/nm (Figure 4a) and another cut along $\nu_W = 0.23$ (Figure 4b). The Kondo temperature (top panels) can be widely tuned by both doping and electric field. And $A^{-1/2}$ (lower panels), the inverse of the mass enhancement, largely follows T^* as expected. Increasing the doping density is expected to strengthen the Kondo effect since there are more conduction holes to screen the local moments; this is consistent with the observed dependence of T^* on ν_W.

Conclusion and Future Steps:

We have realized a Kondo lattice in AB-stacked $MoTe_2$/WSe_2 moiré bilayers. It opens exciting opportunities to study the gate-controlled Kondo destruction transition by extending the Kondo temperature further down to zero, for instance, by reducing the doping density in higher-quality devices or the interaction effect in small-twist-angle bilayers.

References:

[1] Kirchner, S., et al. Colloquium: Heavy-electron quantum criticality and single-particle spectroscopy. Rev. Mod. Phys. 92, 011002 (2020).
[2] Stewart, G. R. Heavy-fermion systems. Rev. Mod. Phys. 56, 755-787 (1984).
[3] Kumar, A., et al. Gate-tunable heavy fermion quantum criticality in a moiré Kondo lattice. Phys. Rev. B 106, L041116 (2022).
[4] Guerci, D., et al. Chiral Kondo lattice in doped $MoTe_2$/WSe_2 bilayers. Sci. Adv. 9. eade7701 (2023).
[5] Mak, K. F., and Shan, J. Semiconductor moiré materials. Nat. Nanotechnol. 17, 686-695 (2022).