Gate-Tunable Heavy Fermions in a Moiré Kondo Lattice

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**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 ($v_w$). 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, $v' = B/(eR_{xy}n_w)$ for $v_w = 0.35$. We obtain $v' \approx -v_w$ for $v_{Mo} = 2$, where the Kondo lattice is not formed. For $v_{Mo} = 1$, below critical magnetic field ($B_c$) we obtain $v' \approx 1-v_w$. It indicates a hole Fermi surface with density of $1 + v_w$.

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
quasiparticle mass enhancement, supports the realization of the Kondo lattice. The Hall measurement also shows that the large Fermi surface with hole density $1 + v_W$ is reduced to a small Fermi surface with hole density $v_W$ 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 $v_W = 0.23$ (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 $v_W$.

### 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:

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