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Title of the Presentation: Tailoring artificial Kondo lattice in van der Waals monolayer crystals

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Short Biography:

Ying-Shuang Fu obtained his Ph. D. from Institute of Physics, Chinese Academy of Sciences in 2008. From 2008 to 2014, he was a postdoctoral researcher at Hamburg University and RIKEN, respectively. He has been a professor of the School of Physics and Wuhan High Field Magnet Center in Huazhong University of Science and Technology since 2014. He is a recipient of Distinguished Young Scientist Program from NSFC, and first scientist of National Key R&D Program of China. He has been focuses on the study of correlated states in low dimensional quantum systems with molecular beam epitaxy and spectroscopic imaging scanning tunneling microscopy under ultralow temperature and high magnetic field.

Abstract:
The heavy fermion physics is dictated by subtle competing exchange interactions, posing a challenge for their understanding. Conventional heavy fermion systems are found in three-dimensional f-electron materials, which is complicated by the crystal and electronic structures. Artificial heavy fermions not only offer new systems that are simple in structure, but also may add desired functionalities. In this talk, I will present our recent progress in realizing artificial heavy fermions in van der Waals (vdW) monolayer crystals or heterostructures that were grown with molecular beam epitaxy. Utilizing low temperature spectroscopic imaging scanning tunneling microscopy, we observed switching behavior of correlated gap in monolayer 1T-$NbSe_2$ showing star-of-David (SD) charge density wave (CDW) pattern. Upon decreasing Se flux, a new quasi-1D CDW order emerges as caused by the incorporation of regularly spaced defect lines introduced into the SD motifs. Coherent Kondo screening is established along stripes, forming a long-sought quasi-1D Kondo lattice at the monolayer limit. We also succeeded in constructing a 2D Kondo lattice composed of monolayer VSe_2 grown on $NbSe_2$, which indicates evident signatures of superconducting heavy fermions via proximity effect from the substrate. Our study realizes artificial Kondo lattices with tailored dimensionality, establishing connection between the heavy fermion physics and 2D materials with desired functionalities.

Kondo lattice depicts a matrix of magnetically coupled local moments that are screened by itinarant electrons, producing low energy excitations with heavy effective mass. Such heavy fermions exhibit multiple intriguing quantum phases, whose mechanism is formidable to interpret. Despite the complexity, one-dimensional (1D) Kondo lattice model has attracted extensive attention, because it is strictly solvable and contains unique quantum critical behavior that is distinct to its 3D counterpart. However, experimental quasi-1D heavy fermion systems are extremely rare. In addition, those compounds are all bulk crystals with complicated atomic structures, whose magnetic moments are from highly localized f-electrons, making their physcial properties hardly tuned. As such, it is highly desrible to explore quasi-1D Kondo lattice behavior in more extended d-electron systems yet possessing simple crystal structure.

For the first time, we realized such NbSe2 with regularly spaced line defects. This system unexpectedly undergoes a new type of striped charge density wave transition, creating a matrix of local moments from d-electrons and itinerant electrons with quasi-1D character. Coherent Kondo screening is found to be established along stripes. Tranversing the stripes, the magnetic moments remain localized. Moreover, prominent modulations in hybridization strength occur around defects in the Kondo lattice along stripes, manifesting expected behavior of Kondo holes. Those physcical properties signify the formation of heavy electron fluids in quasi-1D Kondo lattice systems. This finding unveils unprecedented anisotropic Kondo lattice behavior in monolayer limit, and opens up ample opportunities for tuning the monolayer system with external means. Artifical Kondo lattice systems One-dimensional (1D) Kondo lattice model has attracted special attention in theory, because of its exact solvability and expected unusual quantum criticality. However, such experimental material systems are extremely rare. Here, we demonstrate the realization of quasi-1D Kondo lattice behavior in a monolayer van der Waals crystal NbSe2, that is driven into a stripe phase via Se-deficient line defects. Spectroscopic imaging scanning tunneling microscopy measurements and first-principles calculations indicate that the stripe-phase NbSe2 undergoes a novel charge-density wave transition, creating a matrix of local magnetic moments. The Kondo lattice behavior is manifested as a Fano resonance at the Fermi energy that prevails the entire film with a high Kondo temperature. Importantly, coherent Kondo screening occurs only in the direction of the stripes. Upon approaching defects, the Fano resonance exhibits prominent spatial 1D oscillations along the stripe direction, reminiscent of Kondo holes in a quasi-1D Kondo lattice. Our findings provide a platform for exploring anisotropic Kondo lattice behavior in monolayer limit.

we have successfully fabricated a novel heterostructure, NbSe/Nb/1H-NbSe2, consisting of a NbSe layer on monolayer 1H-NbSe2 with intercalated Nb atoms in the vdW gap between them. Low-temperature scanning tunneling microscopy (STM) and spectroscopy (STS) characterization reveal the Kondo insulator lattice properties formed by the coupling of the periodic local moments carried by the surface Nb atoms with itinerant electrons stemming from Nb-3dz and dx2-y2 and find the theoretically predicted standard spectrum of Kondo insulator. The difference between the Fano-shaped and full-gaped Kondo insulator dI/dV spectra in different regions reveals the effect of the quantum size on the Kondo lattice system. Starting from the Kondo-Heisenberg Hamiltonian, we investigate the impact of sample size on the Kondo ground states of heavy fermions, consistent with experimental observations. Our work presents the first observation of the standard STS spectrum of the Kondo insulator, as predicted by the theory. Additionally, we demonstrate the quantum size effect on the Kondo hybridization term in heavy fermion physics. This effect provides an additional means of modulating heavy fermionic materials, alongside pressure[], temperature[], and doping[]. It is important for controlling the Kondo lattice system to achieve different ground states, as well as strongly correlated quantum phases, such as superconductivity and quantum phase transitions.

Engineering Kondo lattice with tailored functionality is desirable for elucidating the heavy fermion physics. We realize the construction of an artificial Kondo lattice/superconductor heterojunction by growing monolayer VSe_2 on bulk 2H-$NbSe_2$ with molecular beam epitaxy. Spectroscopic imaging scanning tunneling microscopy measurements show the emergence of a new charge density wave (CDW) phase with $\sqrt{3} \times \sqrt{3}$ periodicity on the monolayer VSe_2. Unexpectedly, a pronounced Kondo resonance appears around the Fermi level, and distributes uniformly over the entire film, evidencing the formation of Kondo lattice. Density functional theory calculations suggest the existence of magnetic interstitial V atoms in VSe_2/$NbSe_2$, which play a key role in forming the CDW phase along with the Kondo lattice observed in VSe_2. The Kondo origin is verified from both the magnetic field and temperature dependence of the resonance peak, yielding a Kondo temperature of ~ 44 K. Moreover, a superconducting proximity gap opens on monolayer VSe_2, whose shape deviates from the function of one-band BCS superconductor, but is reproduced by model calculations with heavy electrons participating the pairing condensate. Our work lays the experimental foundation for studying interactions between the heavy fermion liquids and the superconducting condensate.

Mott state in 1T-TaS_2 is predicted to host quantum spin liquids (QSL). However, its insulating mechanism is controversial due to complications from interlayer coupling. Here, we study the charge transfer state in monolayer 1T-$NbSe_2$, an electronic analogy to TaS_2 exempt from interlayer coupling, using spectroscopic imaging scanning tunneling microscopy and first principles calculations. Monolayer $NbSe_2$ surprisingly displays two types of Star-of-David (SD) motifs with different charge transfer gap sizes, that are interconvertible via temperature variation. And, bilayer 1T-$NbSe_2$ shows Mott collapse by interlayer coupling. Our calculation unveils the two types of SDs possess distinct structural distortions, altering the effective Coulomb energies of the central Nb orbital. Our calculation suggests the charge transfer gap, the same parameter for determining the QSL regime, is tunable with strain. This finding offers a general strategy for manipulating the charge transfer state in related systems, which may be tuned into the potential QSL regime.