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Title: Strong coupling and spin-triplet superconductivity in magic-angle twisted trilayer graphene

Abstract:

Moiré superlattices have recently become a playground for exploring correlated physics and superconductivity. Despite the presence of correlated effects in several moiré systems, magic-angle twisted bilayer graphene has remained the only one with robust superconductivity. Here we present a new moiré superconductor, magic-angle twisted trilayer graphene with dramatically richer properties and tunability. By exploring the entire phase space as a function of carrier density, electric and magnetic fields, and temperature, we determine the systems tunable phase boundaries and reveal the intimate connection between the superconducting state and the broken symmetry phase at two carriers per moiré unit cell. The suppression and bounding of superconductivity at the Van Hove singularities is difficult to reconcile with the weak-coupling BCS theory. Furthermore, we can tune the system to be in the ultra-strong coupling regime close to the two-dimensional BCS-BEC crossover, where the Ginzburg-Landau coherence length reaches the average inter-particle distance and T_BKT/T_F ratios are in excess of 0.1. Strikingly, this system also exhibits signatures of spin-triplet superconductivity. Firstly, we find its parallel critical magnetic field to be greatly exceeding the Pauli limit, which cannot be accounted for by the weak spin-orbit coupling in this system. Moreover, we find evidence of reentrant superconductivity at high magnetic fields in excess of 8 tesla, which is reminiscent of the phase diagrams of superfluid He-3 and some heavy-fermion superconductors. Our system establishes a new generation of moiré platform where we can investigate strong coupling and possibly spin-triplet superconductivity with unprecedented tunability.

Two-fold symmetric superconductivity in few-layer $NbSe_2$

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Few-layer samples of transition metal dichalcogenides (TMDs) feature a wide array of properties such as layer-dependent inversion symmetry, valley-contrasted Berry curvatures, and strong spin-orbit coupling (SOC). Among the superconducting TMDs, $NbSe_2$ is profoundly affected by Ising SOC. Ising SOC not only helps stabilize the superconducting state against large in-plane magnetic fields, but in conjunction with other forms of SOC, it could also give rise to exotic superconducting states such as nodal topological superconductivity. This talk will discuss recent transport measurements of few-layer $NbSe_2$, and $NbSe_2$/$CrBr_3$ junctions, studied under in-plane external magnetic fields. Surprisingly, although the crystal lattice has a three-fold symmetry, the magneto-resistance and critical field show a two-fold anisotropy, which is absent in the normal state. We will discuss these results in the context of a competition between the conventional *s-wave* pairing instability characteristic of the bulk and a competing *d-* or *p-wave* instability that emerges in the few-layer limit. These results [1] demonstrate the unconventional character of superconducting pairing in $NbSe_2$ and open the possibility for further discoveries, such as non-trivial topologies, in few-layer TMDs.

[1] Alex Hamill, Brett Heischmidt, Egon Sohn, Daniel Shaffer, Kan-Ting Tsai, Xi Zhang, Xiaoxiang Xi, Alexey Suslov, Helmuth Berger, László Forró, Fiona J. Burnell, Jie Shan, Kin Fai Mak, Rafael M. Fernandes, Ke Wang and Vlad S. Pribiag, *Nature Physics* **17**, 949 (2021).

Quantum Sensing of Moiré Magnetism

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Moiré superlattices of twisted non-magnetic two-dimensional (2D) materials have proven to be highly controllable platforms for engineering exotic correlated and topological states. In this talk, I will present emerging magnetic textures in small-angle twisted 2D magnet chromium triiodide (CrI_3). Employing single-spin quantum magnetometry, we directly visualize nanoscale magnetic domains and periodic patterns, a signature of moiré magnetism, and gain quantitative information on domain size and magnetization. In twisted bilayer CrI_3, we observe the coexistence of antiferromagnetic (AFM) and ferromagnetic (FM) domains with disorder-like spatial patterns pinned by the underlying stacking structure. Remarkably, in twisted double trilayer CrI_3, AFM and FM domains with periodic patterns appear, in good agreement with the calculated spatial magnetic structures arising from the local stacking-dependent interlayer exchange interactions in CrI_3 moiré superlattices. Our results highlight magnetic moiré superlattices as a new platform for exploring emergent magnetic phases.

Interplay between spin-orbit coupling and magnetism at a magnetic van der Waals interface

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Two-dimensional (2D) materials and their integrated superstructures provide emergent phenomena associated with reduced dimensionality, modified lattice symmetry, and enhanced proximity coupling. A remarkable example is Ising superconductivity emerging in a non-centrosymmetric 2D superconductor with broken in-plane inversion symmetry as represented by 2D $NbSe_2$, where strong Zeeman-type spin-orbit coupling (SOC) locks the orientation of the spins of Cooper pairs to the out-of-plane direction, providing exotic non-BCS superconducting states. On the other hand, an interplay between such unique Zeeman-type SOC and magnetism has been largely unexplored.

In this presentation, we will show our recent results on the transport properties of the magnetic van der Waals heterostructures based on 2D $NbSe_2$ and a newly-developed 2D Heisenberg ferromagnet V_5Se_8 [1], and discuss the unique proximity and inverse proximity effects mediated by Zeeman-type SOC [2, 3]. We will in particular focus on the specific regime, where the number of the V_5Se_8 layer was decreased down to the 2D limit so that the transport properties are dominated by $NbSe_2$ [3]. Very interestingly, we found that the sign of the anomalous Hall effect (AHE) of those samples were positive at the lowest temperature, which is opposite to those of the V_5Se_8 individual films. We also found that the AHE signal of those samples was enhanced with the in-plane magnetic fields, suggesting an additional contribution to the AHE signal except magnetization. We verify by band structure calculations that those unprecedented behavior could be well understood by accepting the idea that $NbSe_2$ is in a ferromagnetic/ferrovalley state, where characteristic Zeeman-type SOC plays an essential role.

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Electrically tunable homo bilayer moiré semiconductor probed by exciton spectroscopy

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2D material moiré heterostructure constitute a novel platform to study many body physics of electrons and excitons. Transport study of twisted bilayer graphene revealed rich exotic phase of electrons including from Mott insulator state to superconductivity. On the other hand, optical spectroscopy study revealed the effect of moiré lattice potential on excitons in transition metal dichalcogenide (TMD) heterostructure, but the correlated phase of electrons has been elusive.

In this talk, I will present optical spectroscopy study of homo bilayer TMD moiré heterostructure, and report the observation of strongly correlated incompressible electronic state [1]. We utilized a boron nitride (hBN) encapsulated $MoSe_2$ / hBN (1L) / $MoSe_2$ heterostructure with top and bottom gates, which enable independent control of the chemical potential and the electric field. Tightly bound excitons in TMD interact with Fermi sea carriers by forming exciton-polaron, and we utilized the energy shift of exciton-polaron resonance to detect layer resolved charge configuration by optical means. In low electron density regime, we found periodic chemical potential dependence of carrier filling behavior indicating existence of moiré subband structure (Fig. 1). Tuning the electric field at specific filling around one electron / moiré unit cell results in abrupt interlayer charge transfer, evidencing the emergence of strongly correlated incompressible electronic state. In this incompressible state, we also observe emergence of new excitonic resonances from umklapp scattering, which is evidencing the emergence of periodic charge distribution [2].

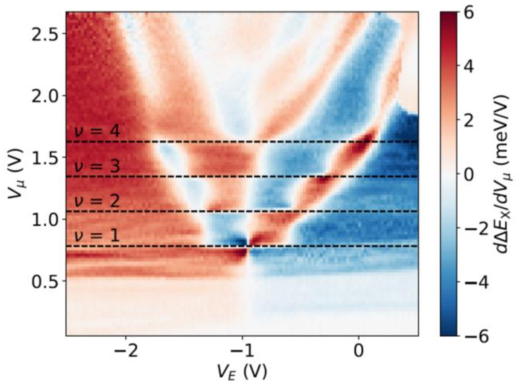

Fig.1 Layer resolved periodic electron filling behavior revealed by excitonic charge sensing.

Exciton spectroscopy also shed light on potential landscape of moiré lattice, and revealed moiré site dependent tunnel coupling of hole carriers (Fig. 2) [3]. Furthermore, quantum tunneling of holes together with electrical biasing assist hybridization of optically excited states, enabled to observe exciton-hole Feshbach resonance (Fig. 2) [3] and interlayer - intralayer hybrid excitons [1].

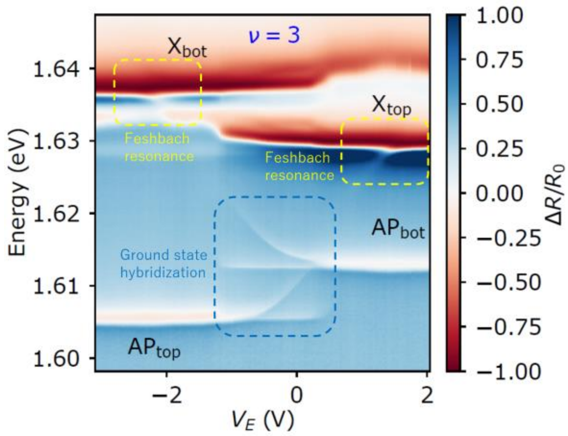

Fig.2 Optically detected moiré site (hole) hybridization and electrically tunable exciton-hole Feshbach resonances.

This highly tunable twisted $MoSe_2$ homo bilayer system separated by a monolayer hBN barrier with weak moiré potential, provides a promising platform for investigating strongly correlated Mott-Wigner physics and Bose-Fermi mixture.

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Exotic quantum phenomena in two-dimensional superconductors

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Two-dimensional (2D) superconductivity has been a vibrant field. Recent discoveries include the Ising superconductivity, the quantum Griffiths singularity, as well as the hotly debated notion of the anomalous metal phase. In this talk, we will present our recent studies on a few representative 2D superconductors. In the first part, we report our investigation of few-layer stanene—ultrathin gray tin (111). Few-layer stanene not only exhibits two-dimensional superconductivity but also topologically non-trivial band structures [1]. Furthermore, they host enhanced in-plane upper critical fields that greatly exceed the conventional limit. We propose that this anomalous behavior stems from a novel type of Ising pairing [2]. In the second part, we study twisted high-T_c Josephson junction. The junctions are realized by artificially stacking two $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO) thin flakes on top of each other. We demonstrate that the Josephson current solely arises from the coupling between the twisted double copper-oxide planes. Notably, the Josephson coupling strength reaches the same level for different twist angles, indicative of an *s*-wave pairing symmetry [3]. Finally, we present our on-going efforts on electric-field controlled lithium intercalations. This technique allows us to control or induce superconductivity. Our recent experiments on titanium diselenide will be discussed [4].

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Designer electronic states in van der Waals heterostructures

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Van der Waals (vdW) heterostructures have emerged as a playground for engineering exotic quantum states not found in naturally occurring materials. In these designer systems, the desired physics emerges through the controlled interactions between the different layers. The use of vdW heterostructures also makes it possible to fabricate device structures potentially allowing further control through e.g. electrostatic gating.

I will outline our recent results on realizing topological superconductivity [1,2] and artificial heavy fermion systems in vdW heterostructures [3]. We use molecular-beam epitaxy (MBE) in ultra-high vacuum for the sample growth and low-temperature scanning tunneling microscopy (STM) for characterization. Topological superconductivity can be realized by combining ferromagnetic $CrBr_3$ on a superconducting $NbSe_2$ substrate [1,2]. This brings together out of plane ferromagnetism, Rashba-type spin-orbit interactions and s-wave superconductivity, which are the necessary ingredients for topological superconductivity. On the other hand, artificial heavy fermion systems can be realized by coupling localized magnetic moments with mobile conduction electrons. We achieve this experimentally by bringing together 1T-TaS_2, where a strong charge-density wave modulation results in a formation of localized electronic states, and normal metal layer 1H-TaS_2 [3]. These examples highlight the versatility of vdW heterostructures in realizing quantum states that are difficult to find and control in naturally occurring materials.

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Title: 2D Magnetic Materials probed by tunneling magetoresistance

Alberto Morpurgo (University of Geneva)

Abstract: In this talk, I will discuss our research on 2D magnetic materials and heterostructures. After a short introduction of the physical systems and of the general questions investigated in this domain of research, I will present results obtained in my group on atomically thin multilayers of different ferromagnetic semiconductors such as CrI_3, $CrCl_3$ (layered antiferromagnets), $MnPS_3$ (antiferromagnetic within individual layers), and $CrBr_3$ (ferromagnetic semiconductors). We use atomically thin crystals of these materials to form tunnel barriers and we obtain information from the measurement of their tunneling resistance as a function of temperature and magnetic field. Examples of observed phenomena and of properties that we extract include: *i)* a giant tunneling magnetoresistance in CrI_3; *ii)* a thorough characterization of the magnetic phase diagram of $CrCl_3$ multilayers; *iii)* the observation of a spin-flop transition in $MnPS_3$ persisting to the ultimate thickness of an individual monolayer, and *iv)* the demonstration that the tunneling magnetoresistance of ferromagnetic CrBr3 barriers depends on magnetic field and temperature only through the magnetization (from well above to well below the Curie temperature). A key conclusion drawn from our work is that measurements of the temperature and magnetic field dependence of the tunneling magnetoresistance allow precise information about the magnetic state of atomically thin crystals to be obtained, something impossible to do with most conventional experimental techniques, not sufficiently sensitive when used on such a small amount of material.

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