High Temperature Superconductivity and Quantum Griffiths Singularity in 2D Superconductors

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By direct transport and magnetic measurements, we provide fist direct evidence for high temperature superconductivity in the 1-UC FeSe films grown on insulating STO substrates with the onset Tc and critical current density much higher than those for bulk FeSe.[1] Furthermore, thickness dependent of superconductivity is carefully studied and superconductor-insulator transition is observed.[2,3] These investigations may pave the way to enhancing and tailoring superconductivity by interface engineering. By both in situ scanning tunneling microscopy/spectroscopy and ex situ transport and magnetization measurements, we find that the two-atomic-layer Ga film with graphene-like structure on wide band-gap semiconductor GaN is superconducting with Tc up to 5.4 K. [4] Furthermore, in three-atomic-layer Ga films, we firstly observe quantum Griffiths singularity in two dimensional (2D) system and superconductors.[5] This discovery is further confirmed in LAO/STO(110) interface superconductors.[6]

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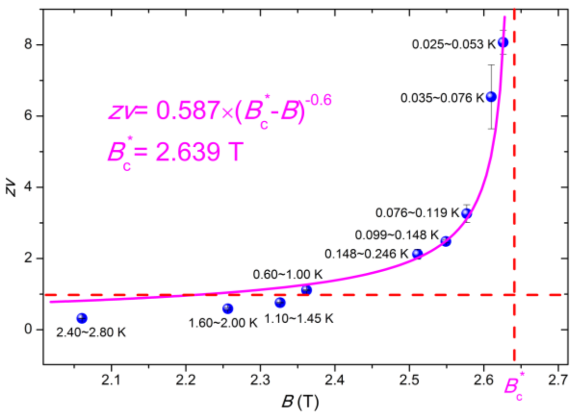

Fig. 1: The divergence of the critical exponent approaching the quantum critical point. *Science* ***350**, 542 (2015)*

Spin Injection, Transport and Conversion in Dirac Electron Materials Systems

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Dirac electrons appear in a material with a linear band structure, such as graphene, topological insulator and bismuth. Because the Dirac electrons exhibit a number of attractive physics, they attract strong attention in solid state physics, especially in spintronics.

Graphene is a pivotal material in spintronics because of its good spin coherence and long-range spin transport at room temperature. On the contrary, graphene was not expected to be an interesting material in spin-orbitronics because of its small spin-orbit interaction. However, recently, conversion from spin current to charge current via the inverse spin Hall effect, which is attributed to the spin-orbit interaction, was realized [1]. The detail of the conversion physics will be introduced.

Bismuth is one of the most intensively studied materials in solid state physics since 19th century, and many effects like the Seebeck effect, the Nernst effect and so on were firstly reported in Bismuth. Because the linear band appears at the L-point, bismuth is also an attractive material in spintronics. We carried out magnetoresistance measurements to clarify multi-carrier properties of bismuth, and investigated the spin conversion physics in bismuth [2,3].

Topological insulators are now the hottest material in physics. From a spintronics viewpoint, detection of the topologically protected surface spin current has been one of the most significant research targets. The group of Wuerzburg reported the detection in a 2-dimenstional topological insulator, and the next target was the detection in a 3-dimenstional topological insulator. We have selected BiSbTeSe, which is a band insulating topological insulator, and detected the surface spin current by using an electrical (potentiometric) method [3].

In this presentation, spin injection, transport and conversion of Dirac electrons in these 3 materials are discussed.

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Tunable negative magnetoresistance in hydrogenated graphene

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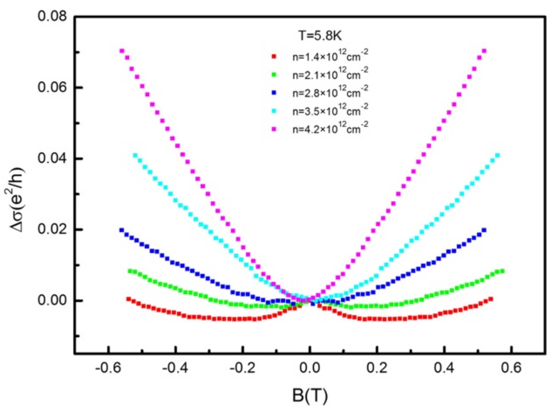
Abstract

The problem of unconventional magnetism in materials without d and f electrons has attracted continuous attention. In particular, a lot of efforts have been devoted to understanding the origin and effects of magnetic moments induced in graphene with structure defects such as missing carbon atoms, absorption of light atoms such as hydrogen or fluorine. We have measured the magnetoresistance (MR) of graphene at low temperature with *in-situ* hydrogenation in ultra-high vacuum environment. The evolution of weak localization and weak anti-localization provide strong evidence that hydrogenation of graphene has introduced local magnetic moment in the electron system, and have substantially increase the spin-orbit interaction of the sample. Large and non-saturating negative MR was also found in hydrogenated graphene which could be tuned by carrier density and sample temperature.



The magneto-conductivity as a function of the small magnetic field at different carrier density of hydrogenated graphene

Ultrafast Photoexcited Carrier Dynamics and Photo Response of 3D Dirac Semimetallic Cd_3As_2

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Three dimensional (3D) Dirac semimetals which can be seen as 3D analogues of graphene have attracted enormous interests in research recently. In order to apply these ultrahigh-mobility materials in future electronic/optoelectronic devices, it is crucial to understand the relaxation dynamics of photoexcited carriers and their coupling with lattice. In this talk, we would first introduce our work of using ultrafast transient reflection measurements to study the photoexcited carrier dynamics in cadmium arsenide (Cd_3As_2), which is one of the most stable Dirac semimetals that have been confirmed experimentally. By using low energy probe photon of 0.3 eV, we probed the dynamics of the photoexcited carriers that are Dirac-Fermi-like approaching the Dirac points. We systematically studied the transient reflection on bulk and nanoplate samples that have different doping intensities by tuning the probe wavelength, pump power and lattice temperature, and find that the dynamical evolution of carrier distributions can be retrieved qualitatively by using a two-temperature model. This result is very similar to that of graphene, but the carrier cooling through the optical phonon couplings is slower and lasts over larger electron temperature range because the optical phonon energies in Cd_3As_2 are much lower than those in graphene.

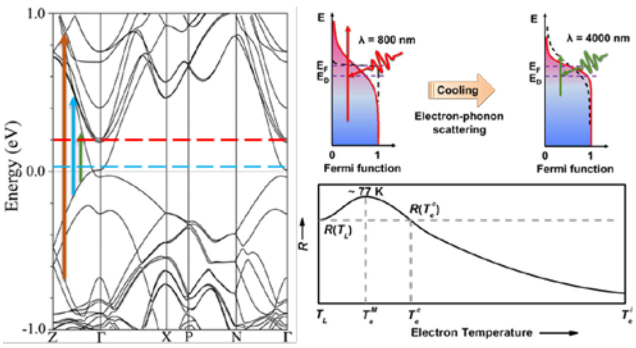

Figure 1. Photoexcited carrier dynamics: (a) Band diagram of Cd_3As_2 and pump/probe photon transition configuration. (b) Schematic diagrams of the dynamical carrier distribution around the Fermi level. (c) Transient reflectivity of bulk at 4 μm as function of instantaneous electron temperature.

Furthermore, based on the fast carrier transient time, we report the realization of an ultrafast broadband photodetector based on Cd_3As_2. The prototype metal-Cd_3As_2-metal photodetector exhibits a responsivity of 5.9 mA/W with response time of about 6.9 ps without any special device optimization. Broadband responses from 532 nm to 10.6 μm are measured with potential detection range extendable to far infrared and terahertz. Systematical studies indicate that the photo-thermoelectric effect plays important roles in photocurrent generation. Our results suggest this emerging class of exotic quantum materials can be harnessed for photodetection with high sensitivity and high speed (~145 GHz) over broad wavelength range.

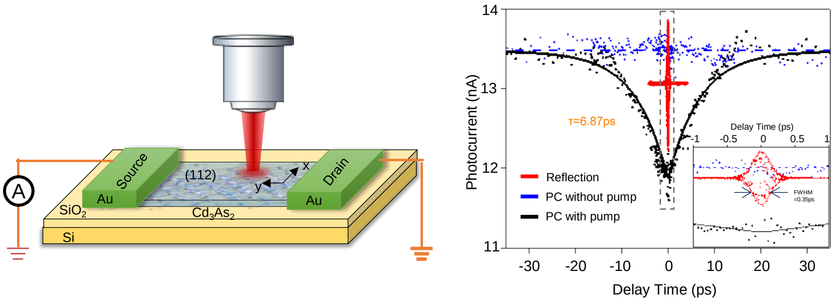

Figure 2. Schematic of scanning photocurrent measurement of Cd_3As_2 nanoplate devices and time-resolved photocurrent measurements of Cd3As2 photodetectors.

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Compass Impurity in Iridates: Tb substitution of Ir in Sr_2IrO_4

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The iridium oxide Sr_2IrO_4 has received a lot of attention for its spin-orbital-entangled Mott insulating state and potential to realize high-temperature superconductivity. A recent experimental study [Phys. Rev. B 92, 214411 (2015)] discovered that just 3% isovalent Tb substitution of Ir can completely suppress the magnetic order in Sr_2IrO_4. We show that upon Tb substitution the interaction between the magnetic moments on the impurity Tb^{4+} ion and its surrounding Ir^{4+} ions is described by a "compass" model, i.e., Ising-like interaction favoring the magnetic moments across each bond to align along the bond direction. Such interaction nucleates quenched magnetic vortices near the impurities and drives a reentrant transition out of the antiferromagnetic ordered phase at low temperatures, therefore would quickly suppress the Neel temperature consistent with the experiment. As a by-product, we propose that the compass model can be realized in ordered double perovskites composed of the spin-orbital-coupled d^5 ions and the half-closed-shell f^7 ions [1].

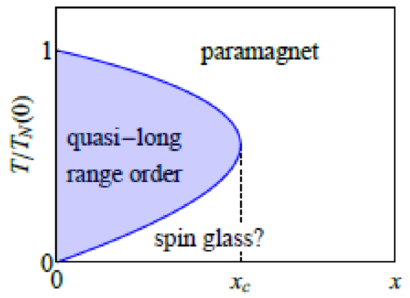

Fig. 1: Schematic phase diagram of a two-dimensional XY spin system with compass impurities of concentration x..

[1] Long Zhang, Fa Wang, and Dung-Hai Lee, Phys. Rev. B, **94**, 161118(R) (2016).

Prominent role of spin-orbit coupling in FeSe revealed by inelastic neutron scattering

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In most existing theories for iron-based superconductors, spin-orbit coupling (SOC) has been assumed insignificant. Even though recent ARPES experiments have revealed an influence of SOC on the electronic band structure, whether SOC fundamentally affects magnetism and superconductivity has remained an open question. Using spin-polarized inelastic neutron scattering, we show that collective low-energy spin fluctuations in the orthorhombic (or "nematic") phase of FeSe possess nearly no in-plane component. Such spin-space anisotropy can only be caused by SOC. It is present over an energy range greater than the superconducting gap $2\Delta_{sc}$ and gets fully inherited in the superconducting state, resulting in a distinct *c*-axis polarized "spin resonance". This result demonstrates the importance of SOC in defining the low-energy spin excitations in FeSe, which helps to elucidate the nearby magnetic instabilities and the debated interplay between spin and orbital degrees of freedom. The prominent role of SOC also implies a possible unusual nature of the superconducting state. I will also present some of our latest results on sulfur doped $FeSe_{1-x}S_x$.

[1] M. Ma *et al.*, arXiv :1610.01277.

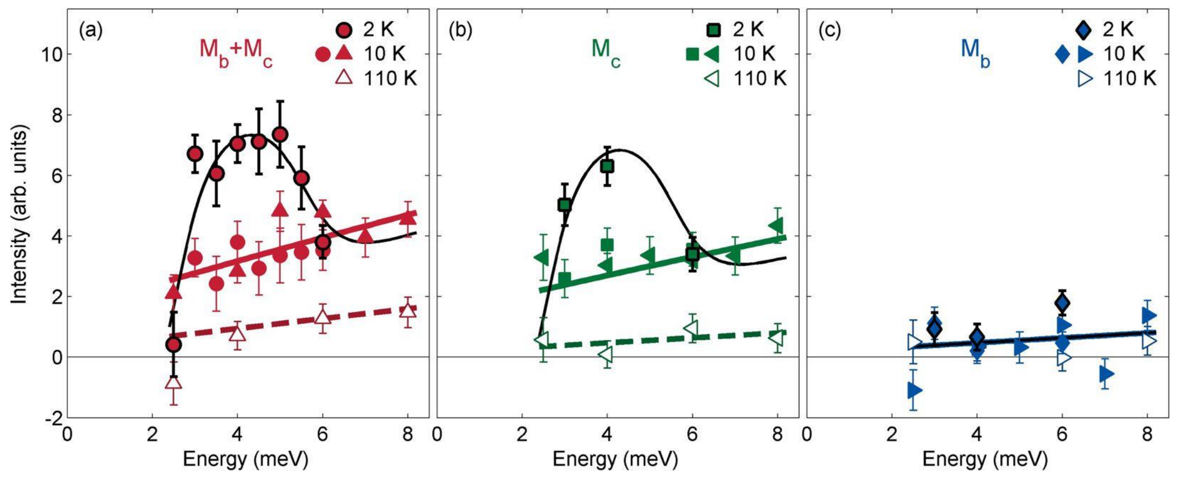

Fig. 1: Experimentally determined spin-excitation components in FeSe near the "striped-antiferromagnetic" wave vector and their evolution with temperature.

Revealing a two-dimensional Ising-like antiferromagnet on a triangular lattice $CeCd_3As_3$

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Geometrically frustrated spin systems have been a subject of considerable theoretical and experimental interest in condensed matter physics because of the potential to host novel ground states and exotic phenomena. The most well-known example of frustration is the antiferromagnetically coupled Ising spins on a two dimensional (2D) triangular lattice that was first studied by Wannier 1950. However, we are not aware of any real material most closely corresponding to the model. In this talk I shall present our very recent work on a layered rare-earth triangular antiferromagnet $CeCd_3As_3$. In this rare-earth antiferromagnet, the Ce local moments form a perfect triangular lattice. Due to the spin-orbital-entangled nature of the Ce local moments, the compound exhibits strong anisotropic antiferromagnetic coupling strengths along c-direction and ab-plane respectively. We show that $CeCd_3As_3$ may represent a rare experimental realization of an antiferromagnetic Ising-like model on a two dimensional triangular lattice and thus provides a prototype example for geometrical frustration.

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Distinctive electronic phase diagram of electron-doped FeSe studied via in-situ surface doping

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Most Iron-based superconductors share a similar Fermi surface topology: the Fermi surface consists of both hole and electron pockets. However, for the heavily electron-doped FeSe, such as $K_xF_{e2-y}Se_2$ and 1 monolayer FeSe thin film, they belongs to another category where the Fermi surface consists of only electron pockets at the zone corner. It is still not clear what the pairing mechanism is for electron-doped FeSe and how it correlates with other iron-based superconductors. Here, utilizing the angle-resolved photoemission spectroscopy (ARPES) and in-situ surface doping, we studied the detailed electronic phase diagram of FeSe and $FeTe_{0.5}Se_{0.5}$ single crystals. The carrier doping was tuned precisely by evaporating potassium onto the cleaved surface. Our result suggests that the pairing symmetry and pairing mechanism of electron-doped FeSe are different from those of iron-pnictides superconductors. The inter pocket scattering between the electron pockets and nematic fluctuation should play a critical role in superconducting pairing.

Spin dynamics in non-collinear spin structure

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Worldwide efforts are underway to create revolutionary and energy-efficient data storage technology such as magnetoresistive random access memory (MRAM). An understanding of spin dynamics in non-collinear spin structure is indispensable for further development of nanoscale magnetic memories. This talk provides a transparent picture of spin dynamics in non-collinear spin structures in ferromagnets, such as magnetic nanowires with domain walls and disks with magnetic vortices, and presents not only technological developments and key achievements but also the unsolved puzzles and challenges that stimulate researchers in the field.

Firstly, the basic concept of non-collinear spin structures is described by introducing a magnetic domain wall in a magnetic nanowire [1]. A magnetic vortex structure in a magnetic disk is also provided as a typical example [2]. The magnetic field-driven dynamics of these non-collinear spin structures are described to illustrate the uniqueness of this system.

Secondly, the electric-current-induced dynamics of domain walls and magnetic vortices are described. One can move a domain wall by current injection into a wire [3-5], and flip the core magnetization in a magnetic vortex using electrical current excitation [6]. The next part focuses on the applications of the current-induced-magnetization dynamics in devices. The basic operations of two kinds of magnetic memories, magnetic domain wall memory [7] and magnetic vortex core memory [8], are demonstrated.

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Title: Dephasing and disorder effects in the topological systems

Speaker: X.C. Xie, Peking University

Abstract:

The influence of dephasing and disorder effects in the topological systems, such as the quantum spin Hall effect (QSHE) system, the surface states of 3D topological insulators, and the Weyl semimetals (WSMs) is studied. For the 2D QSHE system, we find that the quantum conductance plateaus are robust against the normal dephasing but fragile with the spin dephasing, and thus these quantum plateaus only survive in mesoscopic samples. For the surface states of 3D topological insulators, we show that the combination of dephasing and impurity scattering can cause backscattering in the helical states. In WSMs, we predict the Goos-Hänchen and the Imbert-Fedorov shifts exist for the reflection at the interface of two WSMs. We find that the IF shift originates from the topological effect of the system, and can be utilized to characterize the Weyl semimetals, to design valleytronic devices, and to measure the Berry curvature of the system. We also study the impurity scattering and disorder effects in the WSMs. We show that the topological IF shift also influences the single impurity scattering cross-section and gives rise to exotic transport properties of WSMs. Furthermore, we study the disorder induced localization in WSMs, and find three exotic quantum phase transitions.

Direct detection of pure AC spin-current by x-ray pump-probe measurements

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Despite recent progress in spin-current research, the detection of spin current has mostly remained indirect. By synchronizing a microwave waveform with synchrotron x-ray pulses, we use the ferromagnetic resonance of the Py ($Ni_{81}Fe_{19}$) layer in a Py/Cu/$Cu_{75}Mn_{25}$/Cu/Co multilayer to pump a pure AC spin current into the $Cu_{75}Mn_{25}$ and Co layers, and then directly probe the spin current within the $Cu_{75}Mn_{25}$ layer and the spin dynamics of the Co layer by x-ray magnetic circular dichroism. This element-resolved pump-probe measurement unambiguously identifies the AC spin current in the $Cu_{75}Mn_{25}$ layer.

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Electron correlation effects in topological insulators

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We investigate the correlation effect in topological insulators and their topological edge states. We particularly focus on a topological Mott insulator, where the bulk is a correlated topological insulator while the edge state exhibits a typical Mott behavior [1]

We first address a topological Mott insulator in one dimension [2]. We elucidate these properties by examining the bulk topological invariant and the entanglement spectrum of a correlated electron model. We clarify how gapless edge states in a non-interacting topological band insulator evolve into spinon edge states in a topological Mott insulator. Furthermore, we propose a topological Mott transition, which occurs in spin liquid phases in the Mott insulator and is accompanied by a gap closing in the spin excitation spectrum.

We generalize the idea to a two-dimensional system in terms of a double-layer Kane-Mele model [3,4], and show a concrete example of topological Mott insulator in two dimensions. It is clarified how the topological Mott state evolves from the ordinary spin Hall insulating state with increasing the Hubbard interaction at a given temperature and then undergoes a phase transition to a trivial Mott insulating state. With a bosonization approach at zero temperature, we address which collective excitations host gapless edge modes in the topological Mott insulating state. We further demonstrate an intriguing crossover behaviour induced by the interplay between topology and correlation; the edge state change its character from fermionic to bosonic with decreasing temperature.

If time allows, we address the reduction of topological classification due to correlation effects. Two systems are discussed. One is a two-dimensional weak topological insulator [5], which shows the reduction from Z to Z_4. This is shown by studying a double-layer honeycomb lattice model with correlation. The other is a topological superconductor [6], which exemplifies the reduction from Z^2 to ZxZ_8. We show that a heavy-fermion superlattice $CeCoIn_5/YbCoIn_5$ can provide a possible platform to experimentally confirm this reduction.

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Chiral Domain Structure in Superfluid ^{3}He.

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Superfluid ^{3}He is precisely described by spin-triplet-p-wave-Cooper-pair wave function. Symmetry of the wave function is given by a couple of anisotropic axes, namely l-vector in orbital space and d-vector in spin space for the case of ABM state. Those anisotropic axes choose their preferred directions in space following a balance of conflicting orientation energies such as dipole, magnetic anisotropy, gap node orientation on the surface of the container, surface energies originated from the dipole or magnetic anisotropy, and various gradient energies of the order parameter. In the real experimental situation, the anisotropic axes form spatial pattern, which is called Texture. One of the beauties of this system is that NMR measurements provide direct information of the Texture as a resonance frequency distribution. Various topological objects such as quantized vortices and textural solitons are identified through the NMR measurement. However nobody could ever studied the real space location and shape of the topological objects.

Here we present the first-time real-space observation of textural solitons in a thin slab of superfluid ^{3}He-A, which is achieved by our state-of-the-art magnetic resonance imaging technique. The bright horizontal bar shape in the image represents the shape of superfluid ^{3}He-A in a 100μm-thickness-slab-shaped container, while dark vertical lines in the bar represent domain walls which locate in between two adjacent domains. With the aid of much improved magnetic resonance spectroscopic imaging we identified the dark lines as dipole-locked-soliton, which is anchored to the surface of the slab with surface-chiral-domain-wall. The bright quadrilaterals or triangles clumped between the lines are the real images of macroscopic chiral domains in chiral superfluid ^{3}He-A. The chiral domain sturucture is rather stable as far as it is kept at temperatures far below T_C. The domain wall is strongly pinned at the surface of the slab. However we could alter the location of the domain wall by warming to a temperature near T_C and applying flow across the wall. Thus we might be able to manipulate the chiral domain structure in some future.

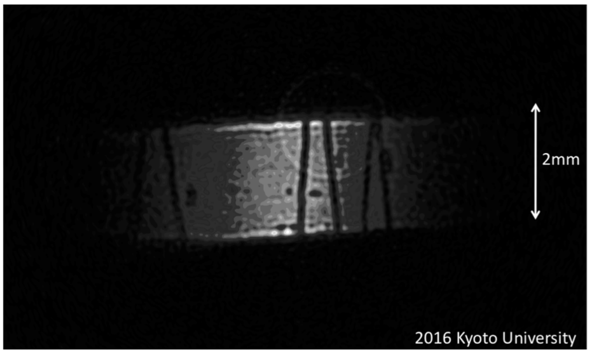

Fig. 1 MRI image of the chiral domain structure in a thin slab of superfluid ^{3}He-A.

Spin-rotation symmetry breaking and triplet superconducting state in the doped topological insulator $Cu_xBi_2Se_3$

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Spontaneous symmetry breaking is an important concept for understanding physics ranging from the elementary particles to states of matter. For example, the superconducting state breaks global gauge symmetry, and unconventional superconductors can break additional symmetries. In particular, spin rotational symmetry is expected to be broken in spin-triplet superconductors. However, experimental evidence for such symmetry breaking has not been conclusively obtained so far in any candidate compounds. We report ^{77}Se nuclear magnetic resonance measurements which showed that spin rotation symmetry is spontaneously broken in the hexagonal plane of the electron-doped topological insulator $Cu_{0.3}Bi_2Se_3$ below the superconducting transition temperature T_c=3.4 K. Our results not only establish spin-triplet superconductivity in this compound, but also serve to lay a foundation for the research of topological superconductivity [1]. We will also present our results on the doping mechanism and pairing symmetry of the doped crystalline topological insulators $In_{1-x}Sn_xTe$ [2].

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Quantum simulation of hydrogen and hydrogen bonds

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Experiments and computer simulations have shown that the melting temperature of solid hydrogen drops with pressure above about 65 GPa[1,2], suggesting that a liquid state might exist at low temperatures. It has also been suggested that this low temperature liquid state might be non-molecular and metallic, although evidence for such behaviour is lacking[3,4]. Here, we report results for hydrogen at high pressures using *ab initio* path-integral molecular dynamics methods, which include a description of the quantum motion of the protons at finite temperatures[5]. We have determined the melting temperature as a function of pressure by direct simulation of the coexistence of the solid and liquid phases[6], and have found an atomic solid phase from 500 to 800 GPa which melts at < 200 K. Beyond this and up to pressures of 1,200 GPa a metallic atomic liquid is stable at temperatures as low as 50 K. The quantum motion of the protons is critical to the low melting temperature in this system as *ab initio* simulations with classical nuclei lead to a considerably higher melting temperature of ~300 K across the entire pressure range considered[7]. Similar simulation technique can also be applied to studies of lithium and hydrogen bonds. If time allows, we will also some recent results on these studies[8-10].

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Quantum capacitance anomalies of two-dimensional non-equilibrium states under microwave irradiation

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We report our direct study of the compressibility on ultrahigh mobility two-dimensional electron system ($\mu \sim 1\times10^7\ \mathrm{cm^2/Vs}$) in GaAs/AlGaAs quantum wells under microwave (MW) irradiation. The field penetration current results show that the quantum capacitance oscillates with microwave induced resistance oscillations (MIRO), however, the trend is opposite with respect to the compressibility for usual equilibrium states in previous theoretical explanations. The anomalous phenomena provide a platform for study on the non-equilibrium system under microwave, and point to the current domains and inhomogeneity induced by radiation. Moreover, the quantum capacitance indication for multi-photon process around j = 1/2 is detected under intensive microwave below 30 GHz.

Hard point contact induced superconductivity on non-superconducting topological materials

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Topological semimetals have become one of most important topics in condensed matter physics. Topological superconductivity is theoretically predicted but complete demonstration by experiments is still missing. By using hard point contact measurements, we firstly detect the unconventional superconductivity on the surface of crystalline 3D Dirac semimetal Cd3As2 [1] with some signatures showing the possibility of topological superconductivity.[2] Furthermore, the hard point contact method has been demonstrated reliable in the study of topological metal Au2Pb [3] and by using same method, we also discovery the superconductivity in Weyl semimetal. Thus, we have developed a new way to realize and detect topological superconductivity.

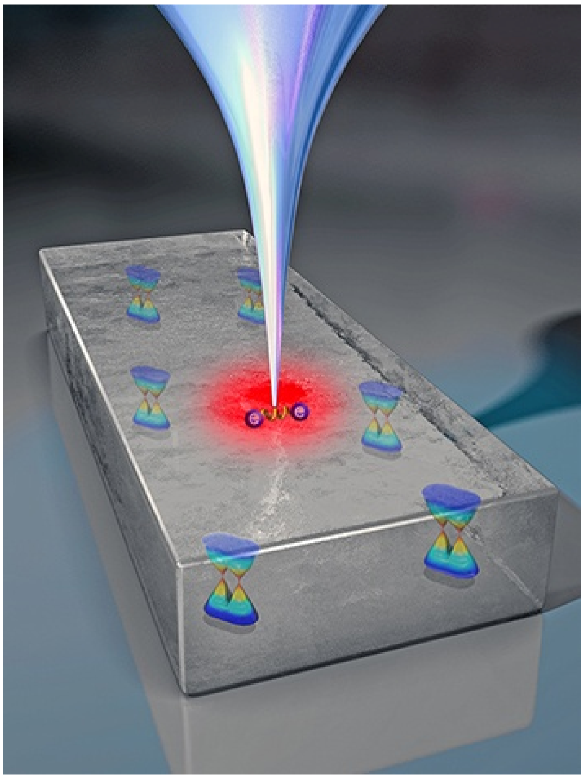

Fig. 1: Unconventional superconductivity induced by hard tip on the surface of topological semimetal. *TOC Image of Nature Materials 2016.*

[1] Physical Review X 5, 031037 (2015)
[2] Nature Materials 15, 38 (2016)
[3] npj Quantum Materials 1, 16005 (2016)

Theory of Weyl and topological superconductors

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We study topological and Weyl superconductivity in strongly correlation electron systems. I will speak about three topics listed below.

(1) 2D topological superconductivity designed by nodal superconductors [1,2]
Search of gapped strong topological superconductivity has been one of the central subjects in the field of topological science. We design the topological superconductivity based on the familiar nodal spin-singlet superconductor.

(2) Breakdown of topological classification in heavy fermion superlattices [3]
It has been shown that the heavy fermion superlattice $CeCoIn_5$/$YbCoIn_5$ [4] is a platform of topological crystalline superconductivity protected by mirror symmetry [5]. We propose the breakdown of topological classification by electron correlation, which can be experimentally realized by tuning the superlattice structure.

(3) Nonsymmorphic superconductivity in UPt_3 [6,7]
A heavy fermion superconductor UPt_3 discovered in 1980's is attracting renewed interest because of its topologically nontrivial properties. Experiments and theories point to the odd-parity spin-triplet superconductivity, which is classified into the E_{2u} representation of D_{6h} point group symmetry. Interestingly, the space group of UPt_3 is $P6_3mmc$ preserving glide and screw symmetries with half translation along the c-axis. We show a variety of topologically nontrivial features of UPt_3 arising from its nonsymmorphic space group symmetry.

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