Russian-Chinese International School "Superconducting functional materials for advanced quantum technologies"

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BOOK OF ABSTRACTS

MIPT

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Quantum-size effects in thin metallic films

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My lecture is devoted to the experimental investigations of local electronic properties of thin Pb(111) films on Si(111)7×7 surface by means of low-temperature scanning tunneling microscopy and spectroscopy (STM/STS). Typical thickness ranges from 10 to 50 monolayers.

The first part of the talk summarizes the main results concerning the effect of quantum-well states for electrons inside Pb(111) films on the differential tunneling conductance dI/dU. Since the spectrum of quantum-well states is determined mainly by the local thickness of the Pb(111) film, one can detect tiny variations of an actual thickness of the Pb film, internal stresses and subsurface defects inside these films based on STM/STS above the Pb(111) film [1, 2]. In particular, we can visualize the hidden parts of the dislocation loops under the sample surface [3]. It is shown that the visible height h of the monatomic step on Pb(111) surface demonstrates oscillatory dependence on bias voltage U. These oscillations are controlled by resonant tunneling of electrons from the STM tip to the Pb(111) film through quantum-well states. We show that the maximum and minimum visible heights correspond to the bias voltages, at which local densities of states for the Pb(111) terraces of different thicknesses are equal [4].

The second part of the talk is focused on the effect of surface states, corresponding to the localized electrons above the Pb(111) surface, on the differential tunneling conductance dI/dU and the rate of tip displacement dZ/dU in the regime of constant tunneling current. The presence of such electronic states leads to the peculiar aperiodic oscillations of both dI/dU and dZ/dU as a function of U (so-called Gundlach oscillations or field-emission resonances). Analysis of the spectrum of field-emission resonances allows us to estimate the local work function [5]. We demonstrate that field-emission resonances are responsible for the periodic oscillations of logarithmic derivative of the tunneling current with respect to the tip height (i.e. $d(\ln I)/dZ$) on bias voltage U. Such periodic variations in the $\ln I{-}Z$ spectra makes it possible an estimation of the absolute height of the tip above the sample surface.

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S-F-N hybrid structures and Josephson junctions for superconducting electronics

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The field of superconducting electronics is perspective for development of high performance and energy-efficient devices, including supercomputers, data-centers, neuromorphic and quantum technologies [1]. At the same time, miniaturization and increasing of performance of the schemes require novel base elements [2]. Also there is a lack of energy-efficient logic and memory elements, as well as tunable linear units. The hybrid S-F-N multilayer structures including superconductor, ferromagnetic and normal metal layers have a potential to become effective basic elements for this purposes. The interplay between superconductivity and ferromagnetism permits to use effects like 0-π transition [3], φ-junction self-biasing [4] or appearance superconducting phase domains [5] for design of the structures.

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Critical temperature of superconductor/antiferromagnet heterostructures

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In this work we study theoretically two different manifestations of the sign-flipping Neel triplet correlations, which are induced in superconductor/antiferromagnet (S/AF) heterostructures by proximity effect [1]. The first one is the oscillating dependence of the superconducting critical temperature of S/AF bilayers on the length of the AF region. It occurs due to the oscillating character of the Neel triplet pair wave function, which in its turn originates from the Umklapp scattering processes at the S/AF interface. This prediction could give a possible explanation for available experimental data [2].

The second issue is the interplay of the Neel triplets with Rashba spin-orbit coupling (SOC) in thin-film S/AF structures. A unique effect of anisotropic enhancement of proximity-induced triplet correlations by the SOC is predicted. It manifests itself in the anisotropy of the superconducting critical temperature with respect to orientation of the Neel vector relative to the S/AF interface, which is opposite to the analogous effect in superconductor/ferromagnet structures. The sign of the anisotropy is controlled by the chemical potential of the superconductor and, therefore, can be adjusted in (quasi)2D structures.

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Predictable gate-field control of spin in altermagnets with spin-layer coupling

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Spintronics, a technology harnessing electron spin for information transmission, offers a promising avenue to surpass the limitations of conventional electronic devices. While the spin directly interacts with the magnetic field, its control through the electric field is generally more practical, and has become a focal point in the field of spintronics. Here, we propose a disruptively new mechanism to efficiently and conveniently accomplish this task. Our method employs two-dimensional altermagnets with valley-mediated spin-layer coupling (SLC), in which electronic states display symmetry-protected and valley-contrasted spin and layer polarization. The SLC facilitates predictable, continuous, and reversible control of spin polarization using a gate electric field. Through symmetry analysis and ab initio calculations, we pinpoint high-quality material candidates that exhibit SLC. We ascertain that applying a gate field of 0.2 eV/˚A to monolayer Ca(CoN)2 can induce significant spin splitting up to 123 meV. As a result, perfect and switchable spin/valley-currents, and substantial tunneling magnetoresistance can be achieved in these materials using only a gate field. These findings provide new opportunities for generating predictable spin polarization and designing novel spintronic devices based on coupled spin, valley and layer physics.

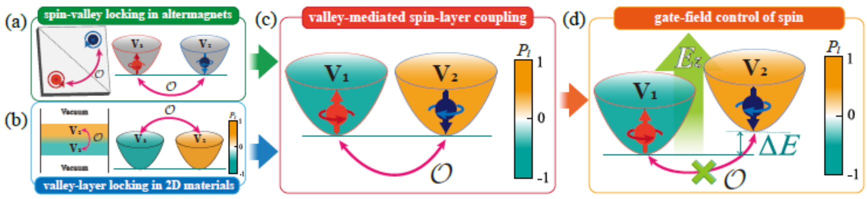

FIG. 1. Illustration of the mechanism of valley-mediated SLC and the electric control of spin. (a) A generic altermagnet with two valleys V_1 and V_2 features intrinsic spin-valley locking, which is protected by certain (magnetic) crystalline symmetry $\mathcal{O}$ rather than time-reversal symmetry $\mathcal{T}$. (b) Meanwhile, a 2D valleytronic material may host $\mathcal{O}$-protected valley-layer locking, where the two valley states have opposite layer polarization (P_l). (c) The combination of spin-valley and valley-layer locking leads to a novel spin-valley-layer coupling: valley-mediated SLC in 2D altermagnets. (d) This effect enables an intuitive, predictable and precise control of the spin polarization by electric gate field.

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Manipulation of deformable micro/nanostructures and their photonic modulations

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More is left to do in the field of flat bands besides the known research efforts. One of these unexplored areas is the flat bands featured in the two-dimensional (2D) van der Waals (vdW) materials. Compared to 3D crystals, the 2D vdW materials with a lower dimension could easily map out prominent flat-band lattice models and provide more straightforward visual evidence for the capture of prime features. Since vdW materials are potentially applicable to the study of flat-band physics, it is urgent to develop a simple and efficient approach to finding realistic vdW crystals with desired flat bands. Here, we utilize a powerful high-throughput tool to screen feasible vdW materials based on the Inorganic Crystal Structure Database. Through layers of filtration, we obtained 861 potential monolayers from 187093 items. Unlike existing screening schemes, a simple, universal rule, i.e., 2D flat-band score criterion, is first proposed to efficiently identify 229 flat-band candidates, and guidance is provided to diagnose the quality of flat bands in 2D systems. From the experimental accessibility perspective, we further provide a sub-catalog of 74 high-quality flat-band candidates among those selected 229 flat-band materials. All these efforts to screen experimental available flat-band candidates will certainly motivate continuing exploration toward the realization of this class of special materials and their applications in material science.

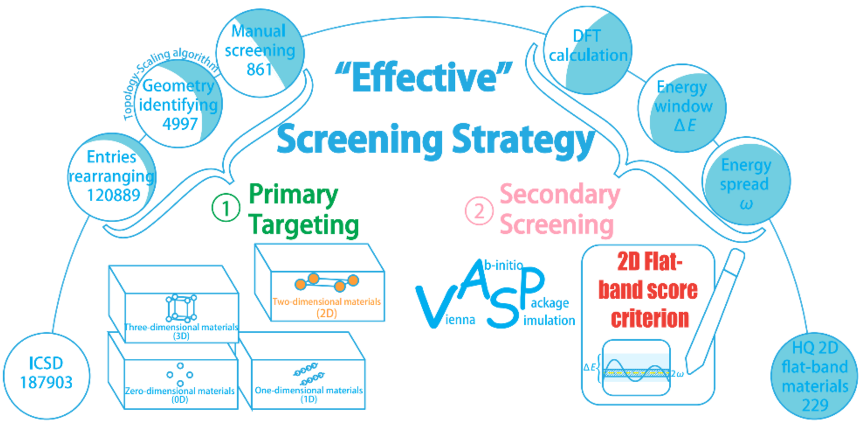

Figure 1. (a) The schematic flowchart of the inventory of van der Waals flat-band materials. This workflow can identify the features of flat bands and illustrate the details of constructing a high-quality (HQ) Flat-band Materials Package by two tiers: primary targeting and secondary screening.

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Tetradimyte-like topological insulators: A Photoemission spectroscopy study

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The discovery of topological phase transitions marked the beginning of one of the most fruitfully developing areas of modern solid-state physics. One of the most studied classes of materials with a nontrivial topology of electronic states are topological insulators (TIs), which in the bulk are a narrow-gap semiconductor with Eg ~ 0.05-0.4 eV, and at the heterointerface with a trivial dielectric they have gapless electronic states. TIs attract interest due to the peculiarities of their electronic structure and a number of new physical effects recently discovered for these objects. The most studied TIs are belong to the so-called tetradimyte-like structure type which may be considered as derivatives of the tetradimyte structure (Bi_2SeTe_2)[1].

Recently, magnetic topological insulators (MTIs) have become the focus of significant scientific interest. Among them, Z2 topological insulators with ordered magnetic moments of embedded magnetic atoms have attracted special attention. One particularly intriguing example is the case of systems with a surface-normal magnetic easy axis coexisting with a topologically nontrivial surface state. To date, the most intensely studied MTIs are $MnBi_2Te_4$ [2] (the so-called 124 phase), a layered compound composed of septuple layers (SLs) with an idealized layer sequence of Te-Bi-Te-Mn-Te-Bi-Te, along with its homological compounds 147 and 1610 etc.

This report will be focused on the experimental study of the electronic and atomic structure of the tetradimyte-like topological insulators. The basics of the topological band theory will also be touched on.

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Spin valves based on antiferromagnet/superconductor/antiferromagnet heterostructures

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Superconducting spin valves, the operating principle of which is based on the proximity effect in superconductor/magnet heterostructures, are a promising object for the study of superconducting spintronics. While superconducting spin valves based on ferromagnetic structures have been well studied, our report focuses on the theoretical description of spin valves based on antiferromagnet/superconductor/antiferromagnetic structures.

An AF/S/AF heterostructure with fully compensated antiferromagnets is considered. The dependence of the critical temperature of a superconductor on the orientation of the Néel vectors of antiferromagnets has been studied, the reason for which is induced triplet correlations of the Néel type [1] in the superconductor, which precisely depend on the mutual orientation of the Néel vectors of the antiferromagnet. The possibility of observing the absolute effect of the spin valve is demonstrated, i.e. switching the system between superconducting and normal states when the angle of misorientation of the Néel vectors changes. The system was studied numerically using the Bogolyubov–de Gennes method and analytically using the semiclassical theory for the Green's function (Eilenberger equation). The effect is considered both in the ballistic limit and in the presence of impurities that suppress Néel triplets. The parity effect is also studied, which consists in changing the sign of the spin-valve effect depending on the parity of the number of atomic layers in the superconductor and confirms the presence of Néel triplet correlations [2].

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Optical properties of superconductors

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My presentation will consist of two parts. In part I, I will briefly review the history of superconductivity (SC). It was discovered in 1911 by Kammerlingh-Onnes in his experiments on the temperature dependence of resistivity of mercury. In 1957, the mechanism of the phonon mediated superconductivity was explained by J.Bardeen, L.Cooper and J.R.Schrieffer (Nobel Prize), and the corresponding theory was named the BCS theory. Since then, numerous attempts have been made to find the material with the highest possible temperature T_c of the SC transition. However, until 1986, the highest T_c that could be achieved was only slightly above 20 K (Nb_3Ge). In 1986, the so-called cuprate superconductors (or high-temperature superconductors, HTSC) were discovered by J.Bednorz and K.Muller (Nobel Prize). The highest T_c of cuprates today exceeds 160 K ($HgBa_2Ca_{m-1}Cu_mO_{2m+2+\delta}$, under 30 GPa). I will briefly mention exotic superconductors, such as low-dimensional organic and spin-ladder systems, heavy fermions, and hydrides, the latter showing transition temperatures close to room temperatures, but at extremely high pressures (hundreds of GPa). In the second part of the presentation, I will focus on the most prominent optical features of a superconductor, as compared to those of a conductor (metal). Optical properties of materials are characterized by frequency (ν) dependent complex characteristics - conductivity $\sigma^*(\nu)=\sigma_1(\nu)+i\sigma_2(\nu)$, permittivity $\varepsilon^*(\nu)=\varepsilon'(\nu)+i\varepsilon''(\nu)$, refractive index $n^*(\nu)=n(\nu)+ik(\nu)$, etc. Using the spectroscopic language, the famous DC (ν=0) resistivity of a SC material, ρ_{DC}, corresponds to an infinite real DC conductivity, $\sigma_1(\nu=0)=1/\rho_{DC},\rightarrow\infty$, i.e., to a delta-function in the conductivity spectrum, $\sigma_1(\nu)=A\delta(0)$. Here A is the spectral weight of the delta-function, which can be expressed in terms of the plasma frequency of the Cooper pair SC condensate, $\nu_{pl}^{SC}=\frac{ne^2}{\pi m}$ (n, e and m are Cooper pairs concentration, electron charge and mass, respectively). Using the Kramers-Kronig transformations, one can find the "optical image" of the zero-frequency delta-function in the permittivity spectrum, $\varepsilon'(\nu)=-\left(\frac{\nu_{pl}^{SC}}{\nu}\right)^2$. It can be seen that by measuring the temperature-dependent dielectric response $\varepsilon'(\nu,T)$ of a superconductor, one can on a quantitative level determine its fundamental characteristics, including the London penetration depth $\lambda_L=\frac{c}{2\pi\nu_{pl}^{SC}}$ (here c is the light velocity). Optical spectroscopy allows to determine one more fundamental characteristic of a superconductor, the SC energy gap Δ, which is detected in the conductivity spectrum $\sigma_1(\nu)$ in the form of a sharp feature indicating breaking of a Cooper pair by the electromagnetic quantum with the energy $h\nu=2\Delta$ (h is Planck's constant). A number of other specific electrodynamic properties of a superconductor will be discussed, and some examples of spectroscopic studies performed at the MIPT Laboratory of terahertz spectroscopy on various SC compounds will be shown. In summary, I will show that optical spectroscopy is an extremely powerful tool that can be used to study the fundamental properties of superconductors, the materials that constitute one of the most remarkable classes of solids. Superconductors have already found an extremely wide range of applications in various fields, and they have fantastic prospects for applications when room temperature superconductivity will be finally realized.

Depth analysis of variational quantum algorithms for the heat equation

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We consider three approaches to solve the heat equation on a quantum computer. Using the direct variational method we minimize the expectation value of a Hamiltonian with its ground state being the solution of the problem under study. Typically, an exponential number of Pauli products in the Hamiltonian decomposition does not allow for the quantum speed up to be achieved. The Hadamard test based approach solves this problem, however, the performed simulations do not evidently prove that the Ansatz circuit has a polynomial depth with respect to the number of qubits. The Ansatz tree approach exploits an explicit form of the matrix what makes it possible to achieve an advantage over classical algorithms. In our numerical simulations with up to $n=11$ qubits, this method reveals the exponential speed up.

Manipulation of deformable micro/nanostructures and their photonic modulations

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Recently, deformable micro/nanostructures show the outstanding performance and wide range of applications. In this presentation, we will introduce the design, fabrication, manipulation, and photonic modulation of deformable micro/nanostructures. Here, these structures can be transformed by capillary force, electrostatic force, and electro-mechanical-chemical (EMC) coupling mechanism. Moreover, we found that deformable micro/nanostructures can be used to achieve the customized optical vortices (in Fig. 1), dynamic color displays, and reconfigurable spectra. Compared to the traditional dynamic metasurface method, our strategy is efficient and practical, which might bring a new opportunity to functional 3D micro/nanostructures with improved optical tunability and customization. In the future, deformable micro/nanostructures provide new ideas for the design of tunable photonic metasurface and metamaterial, as well as a new platform for fabricating functional optical structures. In addition, they can be applied to multifunctional micro- and nano-optoelectronic devices and systems. For example, integrating acousto-optic coupling device and piezoelectric transducer to construct multifunctional MOEMS/NOEMS by means of the varied deformations of the structures, and they also have the application potential to micro-droplet trapping and micro-force sensing.

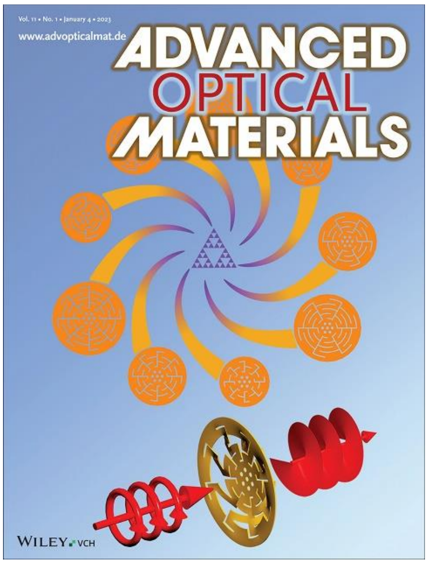

Fig. 1: Deformable nano-kirigami structures with rotational symmetries. The structures are envisioned to provide the capability of conveniently generating optical vortices with improved tunability and customization.

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Proximity effect in a thin-film superconductor/ferrimagnet bilayer

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The proximity effect in a homogeneous ferrimagnetic superconductor, which is also the simplest model of a thin-film superconductor/ferrimagnetic bilayer, has been studied. The dependences of the critical temperature on the magnitude of the exchange field and the degree of non-equivalence of the ferrimagnet sublattices were obtained, and a comparison was made with the limiting cases of a ferromagnet [1] and an antiferromagnet

[2] and two different regimes were discovered depending on the magnitude of the chemical potential. The order parameter on two sublattices is calculated depending on the magnetization value of one of the sublattices and the degree of non-equivalence of the sublattices. For a ferrimagnet, an order parameter unequal on two sublattices ("corrugated") was obtained. Such a superconducting state is not realized in the case of equivalent sublattices with both ferromagnetic and antiferromagnetic types of magnetic ordering. The difference in order parameters on the sublattices and its behavior depending on the magnetization ratio on the sublattices have been studied. The dependences of the anomalous Green's functions of singlet and triplet correlations on magnetization for various ferrimagnets were also obtained and compared with ferro- and antiferromagnets.

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Gasochromic effects in nanostructures based on transition metal oxides and metal catalyst in hydrogen-rich atmosphere

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Due to the development of hydrogen energy technologies and the necessity to ensure safety in industries, there is a need to develop optical hydrogen sensors. Gasochromic materials (for example, WO_3) paired with a catalytic metal (Pd, Pt) are often used as a sensitive element in such sensors [1]. Important research tasks are to determine the fundamental mechanism of gasochromic coloration and to increase the sensitivity and selectivity of sensors to hydrogen [2].

This work presents the results of retrieval the dispersion relation of the dielectric permittivity of tungsten oxide during its gasochromic coloration in a hydrogen-containing atmosphere. The reaction with hydrogen was found to result in the formation of a feature in the dispersion relation of the imaginary part of the WO_3 permittivity, that is associated with an increase in the optical absorption. This feature was approximated with good accuracy by two Gaussian contours related to the formation of oxygen vacancies both on the surface and in the volume of the material.

A one-dimensional resonant nanostructure based on WO_3 was developed and its optical response was studied in air and nitrogen atmospheres containing various concentrations of hydrogen. It was shown that the limit of detection of the nanostructure in air was 100 ppm H_2, and its response was selective to hydrogen with respect to the temperature and humidity of the gas mixture, which was due to the resonant properties of the system.

Using focused laser radiation, Pd/PdO heteronanostructures were formed on the surface of palladium nanofilms. The transformation of the features of their optical properties during the reduction reaction in H_2 was studied–by optimizing the structure of the sensor element, the optical response time was reduced by more than 1000 times.

It was found that the magneto-optical figure of merit of permalloy nanofilms during their oxidation increased by more than one order of magnitude in the near infrared spectral range. The magneto-optical response to hydrogen of a magnetic metal oxide, an oxidized permalloy nanofilm, was demonstrated for the first time. It was experimentally confirmed that the observed gasogyrochromism is a nonreciprocal magneto-optical phenomenon.

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Solving differential equations on a superconducting quantum processor

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Variational quantum algorithms are a promising tool for solving partial differential equations. The standard approach for its numerical solution are finite difference schemes, which can be reduced to the linear algebra problem. We consider three approaches to solve the heat equation on a quantum computer. Using the direct variational method we minimize the expectation value of a Hamiltonian with its ground state being the solution of the problem under study. Typically, an exponential number of Pauli products in the Hamiltonian decomposition does not allow for the quantum speedup to be achieved. The Hadamard test based approach solves this problem, however, the performed simulations do not evidently prove that the Ansatz circuit has a polynomial depth with respect to the number of qubits. The ansatz tree approach exploits an explicit form of the matrix what makes it possible to achieve an advantage over classical algorithms. In our numerical simulations with up to $n = 12$ qubits, this method reveals the exponential speed up.

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Quantum transport in Dirac semimetal-based Josephson junctions

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Three-dimensional Topological Dirac semimetals are unusual quantum materials with massless Dirac fermions and topological Fermi-arc surface states, possessing many exotic transport properties, such as chiral anomaly, Weyl orbit and higher-order topological states. The combination of topological surface state and s-wave superconductor is predicted to host topological superconductivity, which is essential for topological quantum computation. Motivated by this, we studied the quantum transport properties of three-dimensional Dirac semimetal Cd_3As_2 based Josephson junctions. Specifically, 4π-periodic supercurrent, gate tunable topological transition of superconductivity and higher order topological hinge states are observed in Cd_3As_2 based Josephson junctions. These results provide a new route for the manipulation of topological superconductivity states.

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Optical chirality in artificial metamolecules: from nanofabrication to dynamic control

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In this talk, we will briefly introduce some related studies on superconducting functional materials and photonic nanostructures in School of Physics, Beijing Institute of Technology.

As a specific topic, research on optical chirality in artificial metamolecules will be presented in more detail. In the area of nanophotonics, on-chip reconfigurable manipulation of light at nanoscale is one of the most important challenges faced by urgent applications such as photonic integration, metasurfaces and optical metamaterials. Inspired by a traditional Chinese paper-cut named “pulling flower”, here exotic artificial metamolecules are fabricated by a deformable nanofabrication method (named nano-kirigami) in gold nanofilms, which resulted in plasmonic nanostructures with optical reconfiguration capabilities. This method utilized focused ion beam (FIB) instead of knives/scissors to cut a precise pattern in a free-standing gold nanofilm, and used the same FIB instead of hands to gradually “pull” the nanopattern into a complex 3D shape. The “pulling” forces were induced by heterogeneous vacancies (introducing tensile stress) and the implanted ions (introducing compressive stress) within the gold nanofilm during FIB irradiation. By utilizing the topography-guided stress equilibrium within the nanofilm, versatile 3D shape transformations such as upward buckling, downward bending, complex rotation and twisting of nanostructures were precisely achieved. The resulted unprecedented 3D nanogeometries could enable exceptional and flexible functionalities in optical, mechanical, thermal, acoustic, electric, magnetic, and biological areas. As an example, the studies on plasmonic artificial metamolecules with giant optical chirality, polarization conversion property, phase engineering capability and dynamic control will be presented.

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Excitonic Insulator from First-principles

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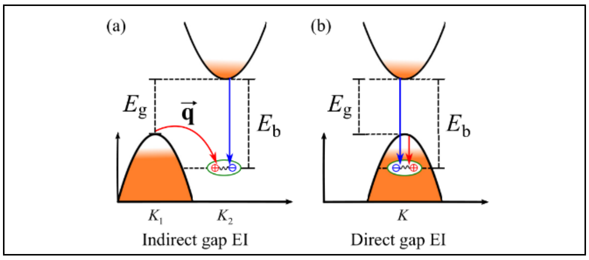
An excitonic insulator holds a many-body ground state similar to a superconductor. Despite over half a century of studies, its convincing evidence is still absent, mainly because of the limited number of suitable materials. In this talk, I will introduce our recent progress in search for excitonic insulators based on first-principles calculations. We propose dark exciton clues as a signal for the occurrence of excitonic instability, which features band-edge-state transitions being optically forbidden. Our first-principles DFT-BSE calculations of a series of two-dimensional semiconductors lend solid support to this principle. We reveal an unusual electronic state (dubbed as half excitonic insulator) in monolayer 1T-MX_2 (M = Co, Ni and X = Cl, Br). Its one spin channel has a many-body ground state due to excitonic instability, while the other is characterized by a conventional band insulator gap. We predict the semi-hydrogenated graphene (known as graphone) as a spin-triplet excitonic insulator with a critical temperature of 11.5 K. We find that a mechanism dubbed as parity frustration prevents excitonic instability in usual topological insulators, and those whose band inversion is independent of spin-orbit coupling are possible candidates. We verify this on four monolayer double-transition-metal carbides (MXenes), which show a robust thermal-equilibrium exciton condensation, being sufficient for topological applications at room temperature.



Pic. 1: Excitonic instability occurs in indirect- and direct-gap systems when the exciton binding energy (E_b) exceeds the one-electron excitation gap (E_g), potentially driving a spontaneous exciton condensation.

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High-temperature Majorana corner modes in a $d + id'$ superconductor heterostructure: Application to twisted bilayer cuprate superconductors

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The realization of Majorana corner modes generally requires unconventional superconducting pairing or s-wave pairing. However, the bulk nodes in unconventional superconductors and the low Tc of s-wave superconductors are not conducive to the experimental observation of Majorana corner modes. Here, we show the emergence of a Majorana corner mode at each corner of a two-dimensional topological insulator in proximity to a d+id′ pairing superconductor, such as heavily doped graphene or especially a twisted bilayer of a cuprate superconductor, e.g., $Bi_2Sr_2CaCu_2O_{8+\delta}$, which has recently been proposed as a fully gapped chiral $d_{x^2-y^2} + id_{xy}$ superconductor with Tc close to its native 90 K, and an in-plane magnetic field. By numerical calculation and intuitive edge theory, we find that the interplay of the proximity-induced pairing and Zeeman field can introduce opposite Dirac masses on adjacent edges of the topological insulator, which creates one zero-energy Majorana mode at each corner. Our scheme offers a feasible route to achieve and explore Majorana corner modes in a high-temperature platform without bulk superconductor nodes.

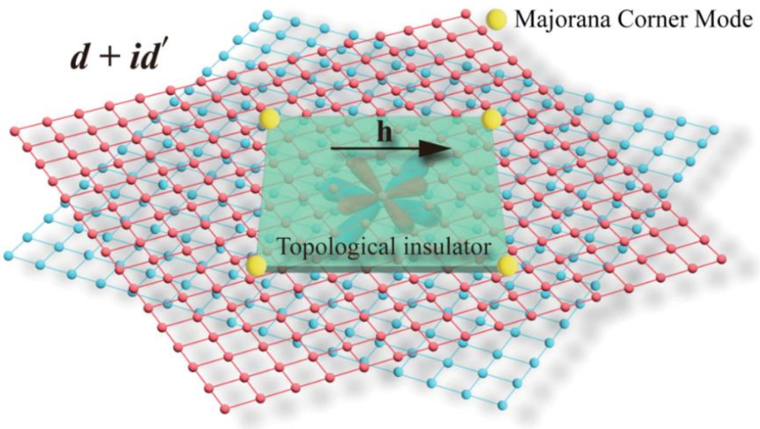

FIG. 1. Schematic diagram of the proposed setup. A heterostructure composed of a 2D topological insulator deposited on a high-T_c fully gapped $d + id'$ pairing superconductor such as a twisted bilayer of cuprate superconductor monolayers and subject to an in-plane Zeeman field. The sphere at each corner represents one zero-energy Majorana corner mode.

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Thermal emission manipulation enabled by nano-kirigami structures

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The nano-kirigami metasurfaces have controllable three-dimensional geometric parameters and dynamic transformation functions, and therefore provide a strong spectral regulation capability of thermal emission. Here we propose and demonstrate a dynamic and multifunctional thermal emitter based on deformable nano-kirigami structures, which can be actuated by electronic bias or mechanical compression. Selective emittance and the variation of radiation intensity/wavelength are achieved by adjusting the geometric shape and the transformation of the structures. Particularly, we develop a thermal management device based on a composite structure of nano-kirigami and polydimethylsiloxane thin film, which can dynamically switch the state of cooling and heating by simply pressing the device. The proposed thermal emitter designs with strong regulation capability and multiple dynamic adjustment strategies are desirable for energy and sensing applications, and inspire further development of infrared emitters.

Key words: Nano-kirigami, Thermal emission, Dynamic, Thermal Management

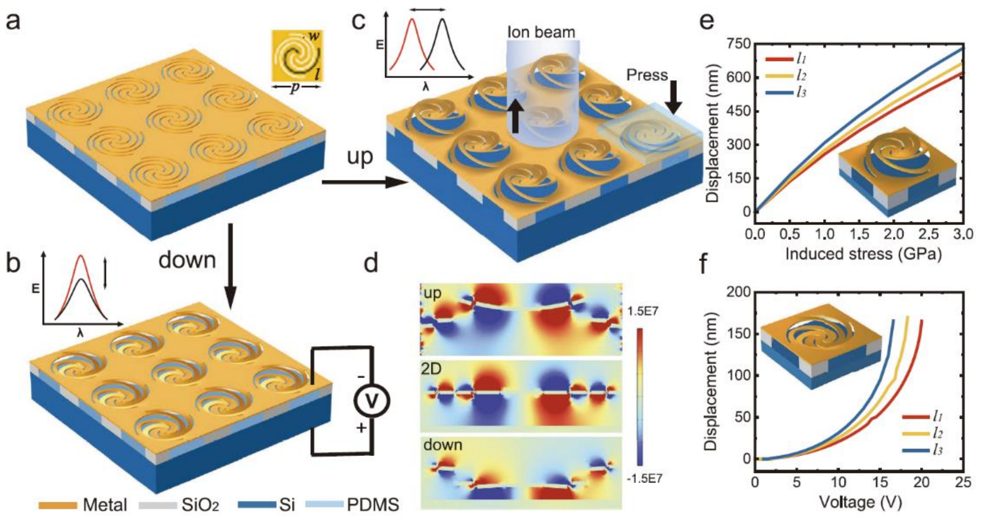

Figure 1. Schematic of the designed nano-kirigami structures and the dynamic driving methods. a) Schematic of a 2D nano-kirigami array and b) its downward 3D state and c) its upward 3D state. d) Normalized E_z distributions in xz plane at the plasmonic resonance wavelength. The mirror symmetry of the field distribution with respect to the xy plane is broken when the nanostructure is deformed from 2D to 3D. e,f) Calculated vertical displacement (Δd) versus applied stress and voltage respectively for structure with different arc length. l_1: 4.6 μm; l_2: 4.8 μm; l_3: 5.2 μm.

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Theoretic study on topological superconductors

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A priority in condensed matter physics is to create topological superconductors with Majorana bound states, which offer a decoherence-free platform for quantum computing. In this talk, I will introduce some of the work we have done on theoretically designing new topological superconductor systems. It mainly contains two aspects. 1. Interaction-driven conventional topological superconductors. We propose a theoretical mechanism for the experimentally discovered unconventional superconducting phenomenon near half-filling in magic-angle bilayer graphene, namely exchange spin density wave fluctuations. We point out the experimentally observed correlated insulating states near half-filling is a non-coplanar chiral spin density wave with non-zero Chern number, i.e., a spontaneous quantum anomalous Hall state. We also propose that the experimentally observed superconductivity may be a chiral topological superconductor with $d+id$ pairing symmetry [1]. 2. Proximity effect induced higher-order topological superconductors. Validated by a new bulk invariant and an intuitive edge argument, we show the emergence of one Majorana Kramers pair at each corner of a square-shaped 2D topological insulator proximitized by an s-wave (e.g., Fe-based) superconductor. We obtain a phase diagram that addresses the relaxation of crystal symmetry and edge orientation and propose candidate materials for experimental realization [2]. In addition, we show the emergence of a Majorana corner mode at each corner of a 2D topological insulator in proximity to a twisted bilayer of cuprate superconductors (e.g., $Bi_2Sr_2CaCu_2O_{8+\delta}$) and an in-plane magnetic field. Such a twisted bilayer was recently proposed as a fully gapped chiral $d_{x2-y2}+id_{xy}$ superconductor with T_c close to its native 90 K. By numerical calculation and intuitive edge theory, we find that the interplay of the proximity-induced pairing and Zeeman field can introduce opposite Dirac masses on adjacent edges of the topological insulator, which creates one zero-energy Majorana mode at each corner [3]. Our schemes offer higher-order and higher-temperature routes for exploring non-Abelian quasiparticles.

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Enhancement of superconductivity and phase diagram of Ta-doped Kagome superconductor CsV_3Sb_5

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Kagome metals AV_3Sb_5 (A = K, Rb, and Cs) have attracted enormous interests due to the coexistence of charge density wave (CDW) order, unconventional superconductivity (SC) and anomalous Hall effect (AHE). In our work, we reported an intensive investigation on $Cs(V_{1-x}Ta_x)_3Sb_5$ samples with systematic Ta doping. The highest Ta doping level was found to be about 16%, which is more than twice as much as 7% in Nb-doped CsV_3Sb_5. With the increase of Ta doping, CDW order was gradually suppressed and finally vanished when the doping level reach to more than 8%. Meanwhile, superconductivity was enhanced with a maximum critical temperature (Tc) of 5.5 K, which is the highest Tc in the bulk crystal of this Kagome system at ambient pressure so far. The $\mu_0 H_{c2}$(T) behavior demonstrates that the system is still a two-band superconductor after Ta doping. Based on the electrical transport measurement, a phase diagram was setup to exhibit the evolution of CDW and SC in $Cs(V_{1-x}Ta_x)_3Sb_5$ system. These findings pave a new way to search for new superconductors with higher Tc in AV_3Sb_5 family and establishes a new platform for tuning and controlling the multiple orders and superconducting states.

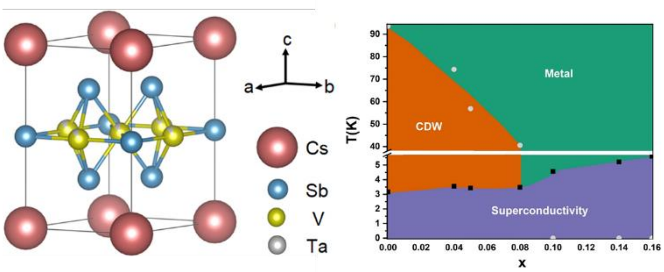

Figure. Side views of $Cs(V_{1-x}Ta_x)_3Sb_5$ crystal structure (left) and phase diagram of the $Cs(V_{1-x}Ta_x)_3Sb_5$ crystals (right)

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Proximate deconfined quantum critical point in $SrCu_2(BO_3)_2$

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The deconfined quantum critical point (DQCP) represents a paradigm shift in quantum matter studies, presenting a “beyond Landau” scenario for order-order transitions. Its experimental realization, however, has remained elusive. Using high-pressure ^{11}B nuclear magnetic resonance measurements on the quantum magnet $SrCu_2(BO_3)_2$, we here demonstrate a magnetic field–induced plaquette singlet to antiferromagnetic transition above 1.8 gigapascals at a notably low temperature, $T_c \simeq 0.07$ kelvin. First-order signatures of the transition weaken with increasing pressure, and we observe quantum critical scaling at the highest pressure, 2.4 gigapascals. Supported by model calculations, we suggest that these observations can be explained by a proximate DQCP inducing critical quantum fluctuations and emergent O(3) symmetry of the order parameters. Our findings offer a concrete experimental platform for investigation of the DQCP.

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In search of emergent quantumness in bioorganic materials

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Despite significantly disordered structure, many bioorganic systems and materials show the ability to carry out processes in which the quantum properties of their participants are clearly manifested. Well-proven phenomena include the tunneling of electrons [1, 2] and protons [3], observed in a number of catalytic processes carried out by biological enzymes. More controversial are the superpositions of excitonic states in biological photoantennas [4], as well as the superposition of the singlet-triplet transition in cryptochrome proteins [5], which is sensitive to a weak external magnetic field. The latter is currently considered as the basis of the most probable mechanism of magnetosensory in migratory birds. In the first part of the lecture, classical results will be presented that serve as proof of the listed quantum processes in biological systems and materials. The second part of the lecture will be devoted to the latest issues of the existence of emergent quantumness, potentially arising in complex systems [6], as well as current and potential opportunities for using the properties of living systems to create new quantum materials [7].

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Noise induced transitions in nonlinear systems

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This lecture introduces some basics of theory of random processes and describes a number on noise-induced effects in nonlinear systems. We consider both effects appearing due to interplay between noise and nonlinearity, such as phase diffusion and noise delayed switching, as well as effects appearing due to interplay between noise and time dependent driving, such as resonant activation, stochastic resonance and driving effects. Some applications to Josephson junction dynamics are considered. In particular, it is demonstrated that resonant activation and noise suppression effects, appearing due to pulse driving, can help in detecting single microwave photons. While phase diffusion effect allows suppressing dark count rate in single photon counters.

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Quantum simulation of spin systems using digital quantum computers

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We point out that digital quantum computers are prospective for the simulation of the dynamics of spin models far from equilibrium, including nonadiabatic phenomena and quenches. The important advantage of these machines is that they are programmable, so that different spin models can be simulated in the same chip, as well as various initial states can be encoded into it in a controllable way. This opens an opportunity to use superconducting quantum computers in studies of fundamental problems of statistical physics such as the absence or presence of thermalization in the free evolution of a closed quantum system depending on the choice of the initial state as well as on the integrability of the model.

In the present lecture, we review the known method of quantum simulation based on the Trotterization of evolution operator and phase estimation algorithm. We provide illustrations, which show the examples of digital quantum simulation of the central spin model using superconducting quantum computer of the IBM Quantum Experience. We found that IBM Q devices are able to reproduce some important consequences of the symmetry of the initial state for the system's subsequent dynamics, such as the excitation blockade. However, quantum circuit depths are currently limited due to quantum gate errors. We also discuss some heuristic methods which can be used to extract valuable information from the imperfect experimental data.

Detecting thermoelectric signals in 2D high-T_c superconductors

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Thermoelectric measurements have always been an important tool for the study of the physics of strongly correlated electron systems, for example, high-T_c superconductors, since the last few decades [1,2]. Regarding the techniques for detecting thermoelectric (TE) signals, a 2ω method is always utilized [3]. Such method is implemented on an on-chip device where deposited metal (normally, Ti/Au) electrodes act as the heater and thermometers. However, it cannot be used at low temperatures because the resistance of the gold film saturates below 10 K due to residual resistance. Here, in our experiments, an optimized on-chip device has been realized, where a narrow strip of gold film is employed as the thermometer and it can work at T < 10 K [4]. Based on this device, we carried out TE measurements on type-II superconducting $NbSe_2$ and ultrathin (≤ 2 UC) cuprate superconductors $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO). We demonstrate a dimensionality cross-over with thickness reduction in the thermally activated behavior of vortices. Furthermore, we observe enhanced thermopower in the ultrathin BSCCO and extend the measurements of Nernst effect down to the lightly doped regime. Our work shows that cuprates in those extreme conditions not only possess unique properties but also help clarify vital issues on high temperature superconductivity.

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Giant enhancement of exciton radiative lifetime by ferroelectric polarization: The case of monolayer TiOCl2

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Exciton binding energy and lifetime are the two most important parameters controlling exciton dynamics, and the general consensus is that the larger the former, the larger the latter. However, our first-principles study of monolayer ferroelectric TiOCl2 shows that this is not always the case. We find that ferroelectric polarization tends to weaken exciton binding but enhance exciton lifetime. This stems from the different effects of the induced built-in electric field and structural distortion by the spontaneous polarization: the former always destabilizes or even dissociates the exciton while the latter leads to a relaxation of the selection rule and activates excitons that are otherwise not optically active. Their combined effect leads to a halving of the exciton binding energy but a substantial increase in lifetime by 40 times. Our results deepen the understanding of the interaction of light with ferroelectric materials and provide new insights into the use of ferroelectricity to control exciton dynamics.

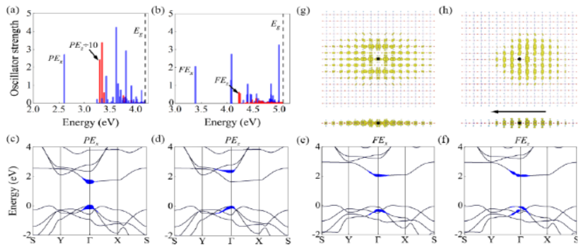

FIG. 1: The calculated exciton energy spectrum inside the quasiparticle gap (Black vertical dashed lines) and the corresponding relative oscillator strength by solving the BSE under the incident light polarization along x- and z-axis for monolayer $TiOCl_2$, respectively, in the (a) paraelectric and (b) ferroelectric state. The BSE fatband structure for the (c) PE_x, (d) PE_z, (e) FE_x, and (f) FE_z exciton. It is superimposed on the PBE one-electron band to visually inspect what kind of electron and hole states dominates the contribution to the very exciton. See the main text for details. The thicker the blue line, the higher the contribution. Real-space exciton wave functions modulus of (g) PE_z and (h) FE_z excitons, with the hole fixed at the center (the black dots). Black arrow denotes the direction of the built-in electric field in the ferroelectric state.

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Gate-tunable transport in van der Waals topological insulator Bi_4Br_4 nanobelts

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Bi_4Br_4 is a quasi-one-dimensional van der Waals topological insulator with novel electronic properties. Several efforts have been devoted to the understanding of its bulk form, yet it remains a challenge to explore the transport properties in low-dimensional structures due to the difficulty of device fabrication. Here we report for the first time a gate-tunable transport in exfoliated Bi_4Br_4 nanobelts. Notable two-frequency Shubnikov–de Haas oscillations oscillations are discovered at low temperatures, with the low- and high-frequency parts coming from the three-dimensional bulk state and the two-dimensional surface state, respectively. In addition, ambipolar field effect is realized with a longitudinal resistance peak and a sign reverse in the Hall coefficient. Our successful measurements of quantum oscillations and realization of gate-tunable transport lay a foundation for further investigation of novel topological properties and room-temperature quantum spin Hall states in Bi_4Br_4.

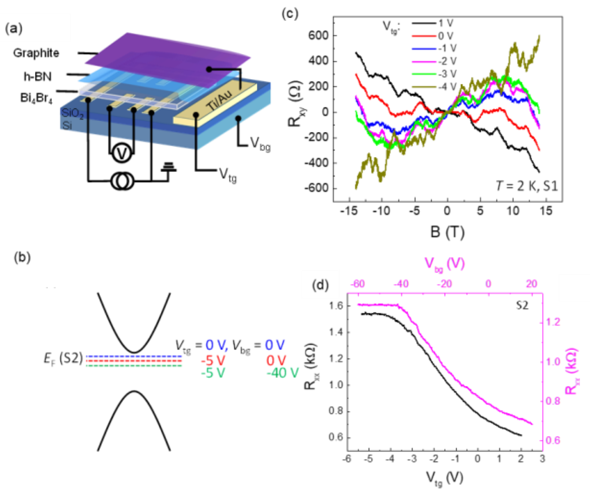

Fig. 1 **Gate-tunable transport properties.** (a) Schematic of the Bi_4Br_4 nanobelt device and measurement configuration. (b) Schematic bulk band structure and the downward shift of Fermi level by applying negative V_{tg} and/or V_{bg}. (c) Field dependence of Hall resistance at different V_{tg} measured at 2 K. (d) Top-gate (black) and back-gate (magenta) dependence of R_{xx} measured at T = 2 K.

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Peculiar properties of a dirty superconductor/low resistive normal metal hybrid

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In many pnictides the superconductivity coexists with ferromagnetism in an accessible range of temperatures and compositions. Recent experiments revealed that when the temperature of magnetic ordering T_m is below the superconducting transition temperature T_c, highly non-trivial physical phenomena occur. We investigate and discuss the existence of a temperature window, situated between T_m and T_c, where these intrinsically type-II superconductors are in the intertype regime. We explore analytically and numerically its rich phase diagram characterized by exotic spatial flux configurations - vortex clusters, chains, giant vortices and vortex liquid droplets - which are absent in both type-I and type-II bulk superconductors. The intertype regime in such pnictides is almost independent of microscopic parameters, and can be achieved by simply varying the temperature. This opens new routes for experimental studies of the intertype superconductivity scarcely investigated to date.

Spectromicroscopic study of the nontrivial topological phase of graphene

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Today graphene remains one of the most intensively researched materials due to its high potential for application in 2D electronics and spintronics. Even though graphene in its quasi-freestanding state is a non-magnetic material with weak spin-orbit interaction (SOC), its electronic properties can be significantly modified upon contact with the atoms of the substrate. For example, the interaction of graphene with heavy atoms can lead to an increase in SOC in graphene, which in turn makes it possible to efficiently generate spin currents based on the spin Hall effect and its quantum version [1]. On the other hand, the combination of strong spin-orbit interaction and magnetism is a necessary condition for observing the quantum anomalous Hall effect [2]. Such a combination can be realized in the magneto-spin-orbit (MSO) graphene at the Au/Co(0001) interface, which not only provides conditions for the implementation of the magnetic proximity effect and the giant Rashba effect [3], but also allows to preserve the linear nature of the dispersion of electron bands near the Fermi level and the ultrahigh mobility of charge carriers.

In this work, calculations within the framework of density functional theory (DFT) have shown the presence of ferrimagnetic order in the A and B sublattices of graphene induced by the dislocation loops in Au/Co interface [4]. Such magnetic ordering of the system along with Rashba spin–orbit coupling induced by Au, as it turned out, leads to the appearance of a band gap in the K-point of the Brillouin zone of graphene and the asymmetry of its spin texture. At the same time our tight-binding calculations indicate that graphene in such a system can exhibit non-trivial topological properties that can be used to realize the Hall effect of circular dichroism and create an infrared detector of circularly polarized radiation based on graphene [4,5].

However, it is worth noting that the MSO graphene reveal one important problem of experimental study of such systems. Due to the very small magnetic moments of carbon atoms (the presence of which, however, significantly affects the electron and spin structures of the MSO graphene), the study of the magnetic order of graphene by standard methods represents an unsolvable task. In this work by modeling the spatial and energy distribution of the electron density, it was shown that the magnetism of carbon atoms manifest itself in the data of scanning tunneling spectroscopy (STS). Modeling of STS data and its comparison with the experimental results gives us strong confidence in the induction of the ferrimagnetic state in graphene on the Au/Co(0001) substrate and makes it possible to estimate the magnitude of the energy gap in its band structure.

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Microwave generator based on the Josephson junction

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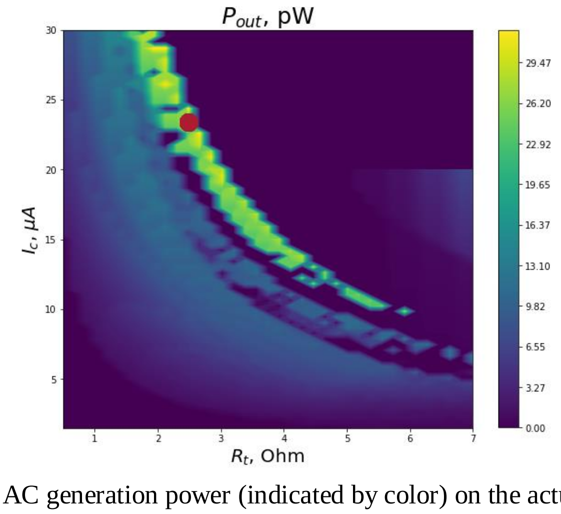
Physical systems used for quantum computing operating in the microwave range require advanced control electronics, and the use of integrated components operating at the temperature of quantum devices is potentially beneficial.

In this paper, we consider a generator consisting of a Josephson junction, a microwave resonator, a shunt capacitance and a resistance. Such a generator operates at a temperature of 20 mK at a frequency corresponding to the control of qubits. The aim of the work is to determine the range of generator parameters in which stable generation is possible by numerical solution of the system dynamics equations, the manufacture of individual generator elements, as well as the search for its optimal parameters using modeling taking into account the obtained generator elements.

As a criterion for the appearance of alternating current generation, the condition described in [1], [2] was used. To calculate the impedance, the method proposed in [3] was used, in normalized values:

$$Z_w = R_w + jX_w = \left(\frac{1}{Ti_w}\right)\int_0^{T\to\infty} \dot{\varphi} e^{jwt} dt \qquad (1)$$

As a result of this work, an analysis of the possibility of generation at different values of the McCumber parameters and the generator frequency normalized to the critical frequency of the Josephson transition is provided. During the work, samples of planar capacitors and normal resistance were manufactured and measured. Using the measured characteristics, the possibility of generating and the power of such a generator manufactured with a simpler planar technology is estimated using simulation.



Pic. 1: The dependence of the AC generation power (indicated by color) on the actual system parameters obtained during operation. The maximum possible power is highlighted with a red dot.

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Electronic and spin structure of quantum materials probed by angle-resolved photoemission

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Angle-resolved photoemission spectroscopy (ARPES) is one of the most direct and powerful methods of studying the electronic structure of solids. By measuring the kinetic energy and angular distribution of the electrons photoemitted from a sample, one can obtain detailed information on both the energy and momentum of the electrons propagating inside a crystalline material. This is of high importance for uncovering the relation between electronic, magnetic, and chemical properties of solids. By analyzing angular distributions of core-level photoelectrons, additional information on the atomic structure can be obtained using a photoelectron (PED) diffraction technique.

Here, we provide guidance on using photoemission spectroscopy to study the electronic structure and related properties of materials using the examples of 2D materials, such as graphene and MoS_2, and layered crystals of lanthanide compounds LnT_2X_2, where Ln is a rare-earth element, T – transition metal and X = Si or P. Some of these materials exhibit strongly correlated electronic behavior and unusual magnetic properties. We demonstrate the capabilities of using ARPES and PED techniques to reveal the features of the electronic and spin structure of bulk and surface electronic states, spin-orbit interaction effects, changes in the valency of 4f elements, differences in the magnetic properties of surface layers from bulk ones, changes in the crystal field near the surface and corresponding changes in the direction of 4f magnetic moments, magnetic proximity effects, electronic correlations and structural characteristics of quantum materials [1-5].

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Intertype superconductivity and current-induced self-organization of mixed superconducting states

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The intermediate mixed state in intertype superconductors is characterized by special vortex interactions, repulsive at short but attractive at long distances while having a significant multi-vortex component [1]. The result is a two-phase domain structure, sensitive to smallest changes in external factors such as magnetic field and temperature [2,3]. Enhanced sensitivity facilitates a large variety of qualitatively different vortex patterns [4]. We discuss results of small angle neutron scattering (SANS) measurements supported by theoretical modelling that shed light on how the vortex matter changes when the current is applied [5]. Influence of the current is particularly interesting as it breaks the symmetry of the mixed state.

We demonstrate that irrespective of its initial profile, the intermediate mixed state rearranges itself into a superstructure of stripes elongated perpendicular to the current flow. The rearrangement is facilitated by a peculiar way the current acts on vortices in an inter-type superconductor. In particular, vortices cannot be regarded isolated, and the action of the Lorentz as well as drag forces on them strongly depend on their spatial configuration. This creates a spatial gradient of vortex velocities leading to fast self-organization of the vortex matter into a superstructure of parallel stripes.

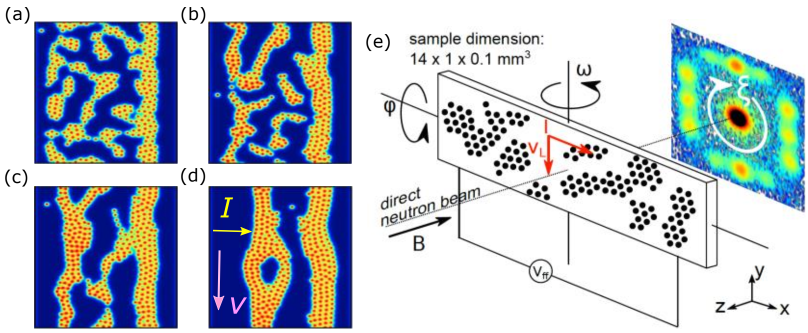

Fig. 1: (a) - (d) Snapshots of the time evolution of the vortex matter in the intermediate mixed state induced by the applied current *I*, here vortices move in the v direction. (e) A sketch of the neutron scattering experiment with the rocking angles ω and φ and the SANS image of the formfactor of the vortex pattern.

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Peculiar properties of a dirty superconductor/low resistive normal metal hybrid

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In my talk I will discuss properties of a superconducting hybrid composed of thin dirty superconducting and low resistive normal metal films. Due to large difference in resistivities and, hence, diffusion coefficients it has peculiar superconducting properties which are absent in ordinary superconductors. First of all SN bridge/strip has large nonlinearity of kinetic inductance (it may change by several times in presence of the current) which allows one to use it in different applications (single photon detectors, parametric amplifiers, sensors of the magnetic field/ current). Secondly, SN strip placed in in-plane magnetic field demonstrates large difference of critical currents, flowing in opposite directions (superconducting diode effect) and large difference of kinetic inductance which is a manifestation of finite momentum state, having an orbital nature [1]. In the end of my talk I will show that SN bridge connected either with normal or superconducting leads may be a host of so called nascent vortices which have properties of ordinary Abrikosov vortices but having a zero vorticity.

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Crystal growth and physical properties manipulation of quantum materials

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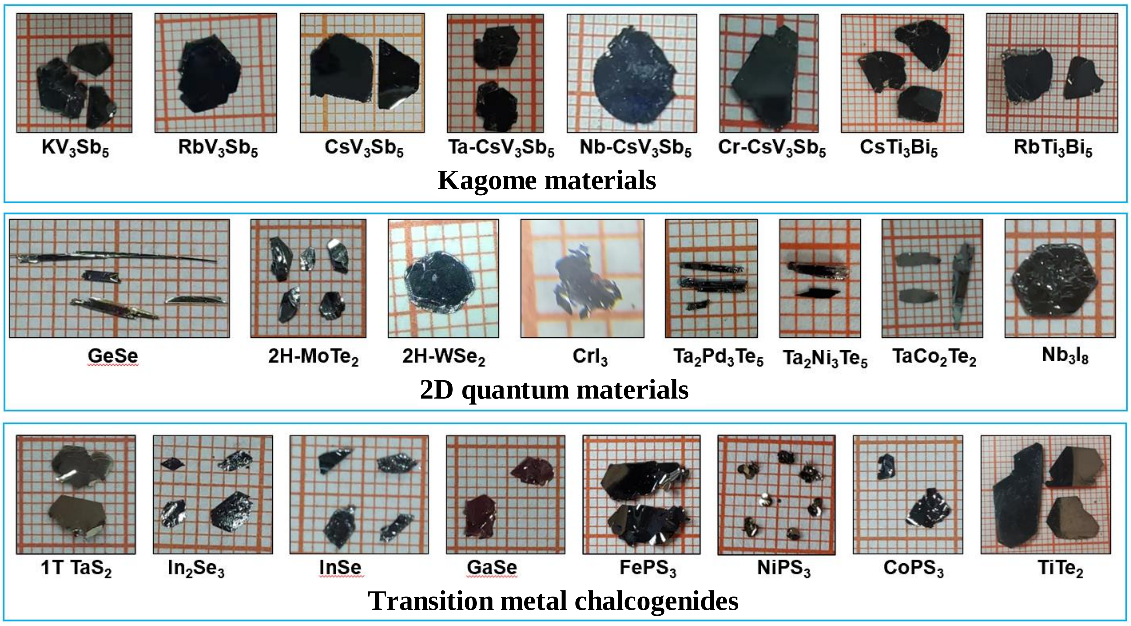
High-quality quantum material single crystals not only play an extremely important role in the basic research, but also act as a prerequisite for the potential application in the future. In this talk I would like to present the crystal growth of variety of novel quantum materials, including topological materials, Kagome superconductors, layered 2D materials and so on. I will also present some basic knowledge of crystal growth at the beginning of the talk. Then, some of our efforts in manipulating physical properties of some interesting quantum materials will be demonstrated. Finally, I will present some new results on exploring of possible topological superconductors by applying high external pressure based on topological insulators.



Pic. 1: Parts of quantum material single crystals grown by our group

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Charge-4e SC and Chiral Metal Phases in the Twisted-Bilayer Quasicrystals

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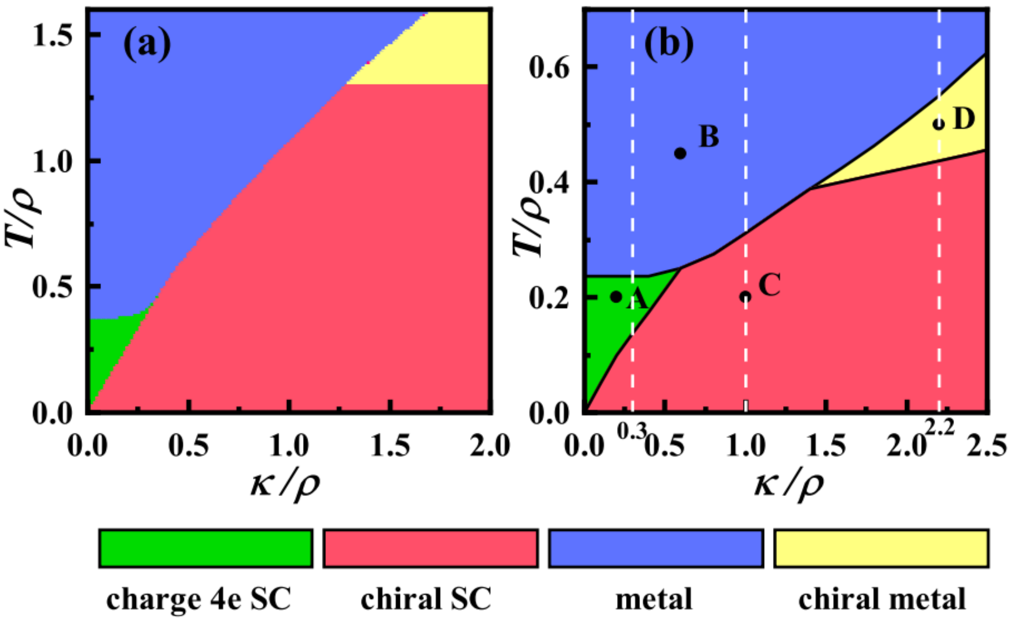
The charge-4e superconductivity (SC) formed via condensation of electron quartets, characterized by half flux quantization, has attracted many interests recently. A previously proposed mechanism for the formation of this exotic type of SC is to emerge as the vestigial phase above the T_c of a multi-component pairing state. Currently, its material realization is a big challenge. Here we propose that the charge-4e SC, in together with the chiral metal, can emerge as the vestigial phases above the chiral topological SC (TSC) ground state in the twisted-bilayer quasicrystals (TB-QC) [1]. The TB-QC represents a class of materials made through stacking a homo-bilayer with the largest twist angle, exampled by the 45 degree-twisted bilayer cuprates and 30 degree-twisted bilayer graphene. When each mononlayer hosts a pairing state with the largest pairing angular momentum, e.g. d-wave for the cuprates or f-wave for some members in the graphene family, our combined Ginzburg-Landau theory and microscopic calculations reveal that the second-order interlayer Josephson coupling (IJC) would drive d+id or f+if chiral TSC in the TB-QC [2]. Further more, above the T_c of the chiral TSC, either the total- or relative- pairing phase of the two layers can be unilateral quasi- ordered or ordered. In the form case, a Cooper pair from the top layer pairs with a Cooper pair from the bottom layer to form the charge-4e SC; in the latter case, a time-reversal symmetry breaking chiral metal phase is formed. Based on a thorough symmetry analysis, we arrive at the low-energy effective Hamiltonian describing the pairing-phase fluctuations. Our combined renormalization group and Monte-Carlo studies reveal the presence of the charge-4e SC and chiral metal phases in certain regimes in the phase diagram. These vestigial phases are characterized by various temperature-dependent quantities and spatial-dependent correlations.



Phase diagram obtained via (a) RG and (b) Monte-Carlo

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Influence of magnons on the superconducting state in superconductor-magnet heterostructures

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It is well known that the proximity effect in thin-film hybrid superconductor/ferromagnetic insulator structures provides the suppression of the superconductivity [1] and Zeeman splitting of the density of states in the superconductors [2]. In this work we investigate the influence of ferromagnetic magnons on this effect. The density of states in the superconductor (DOS) and the quasiparticle spectra are calculated in the framework of Gor’kov Green’s function approach (Fig. 2). It is obtained that the interaction of superconducting electrons with magnons can result in a decrease of the Zeeman splitting of the DOS coherence peaks. It also inverts the ratio between the internal and external coherence peaks and smears the external peaks. The temperature dependence of the observed DOS characteristic features is investigated. It is demonstrated that quasiparticle spectra are also strongly modified by the electron-magnon interaction revealing characteristic kinks (Fig. 1). The sensitivity of the results to the choice of materials and relevance to experiments are discussed.

The support by RSF project No. 22-42-04408 is acknowledged.

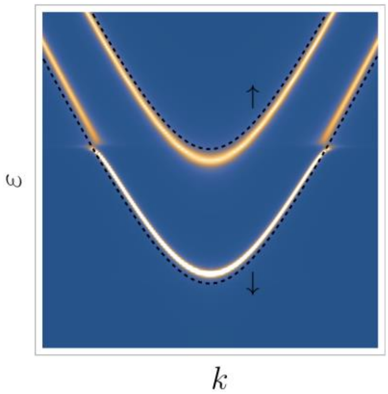

Fig. 1. Quasiparticle spectra. Dashed lines are the branches of the standard spectra of the superconductor; solid lines are for the branches of the spectra, which are modified by the magnon influence

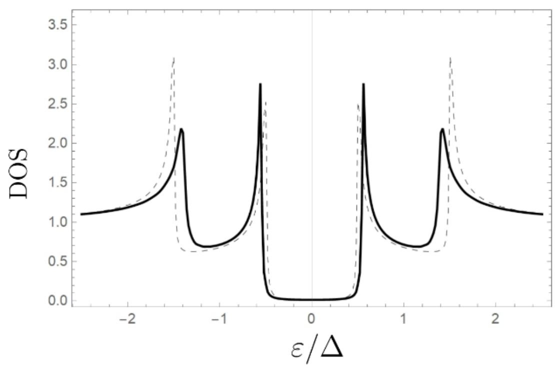

Fig.2. DOS. Dashed line is for the standard DOS of a superconductor; solid line is for the DOS, which is modified by the electron-magnon interaction

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