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Multifractally-enhanced superconductivity in two-dimensional systems with spin-orbit coupling

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The interplay of Anderson localization and electron-electron interactions is known to enhance superconductivity due to the multifractality of electron wave functions. We develop [1] the theory of multifractally-enhanced superconducting states in two-dimensional systems in the presence of spin-orbit coupling. Using the Finkel'stein nonlinear sigma model, we derive the modified Usadel and gap equations that take into account renormalizations caused by the interplay of disorder and interactions. Multifractal correlations induce energy dependence of the superconducting spectral gap. We determine the superconducting transition temperature and the superconducting spectral gap in the case of Ising and strong spin-orbit couplings. In the latter case, the energy dependence of the superconducting spectral gap is convex whereas in the former case (as well as in the absence of spin-orbit coupling) it is concave. Multifractality enhances not only the transition temperature but, in the same way, the spectral gap at zero temperature. Also, we study mesoscopic fluctuations of the local density of states in the superconducting state. Similarly to the case of normal metal, spin-orbit coupling reduces the amplitude of fluctuations.

This work is an extension of a recent article [2], in which by the means of the renormalization group approach within the nonlinear sigma model, the theory of a multifractal superconducting state in thin films has been developed.

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T02

Turbulence Hierarchy and Multifractality in the Integer Quantum Hall Transition

We offer a new perspective on the problem of characterizing mesoscopic fluctuations in the interplateau regions of the integer quantum Hall transition. We found that longitudinal and transverse conductance fluctuations, generated by varying the external magnetic field within a microscopic model, are multifractal and lead to distributions of conductance increments (magnetoconductance) with heavy tails (intermittency) and signatures of a hierarchical structure (cascade) in the corresponding stochastic process, akin to Kolmogorov's theory of fluid turbulence. We confirm this picture by interpreting the stochastic process of the conductance increments in the framework of H- theory, which is a continuous-time stochastic approach that incorporates the basic features of Kolmogorov's theory. The multifractal analysis of the conductance "time series," combined with the H-theory formalism, provides strong support for the overall characterization of mesoscopic fluctuations in the quantum Hall transition as a multifractal stochastic phenomenon with multiscale hierarchy, intermittency, and cascade effects. (Phys. Rev. Lett. 128, 236803 – Published 10 June 2022)

Quantum thermodynamics with Repeated Interactions

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We consider a thermodynamic process controlled by an external agent in which a quantum system is iteratively coupled to a thermal environment for a lapse of time and then decoupled. During these time intervals, heat may flow to the system, but also work is performed on the system. This framework is called the "repeated interaction framework" [1] and its thermodynamics has been studied in [2, 3, 4, 5]. We discuss applications of this thermodynamic framework for energy-storing processes in finite quantum systems [6] and in a cavity QED setup. We then explore similar ideas for storing energy in a quantum system that is strongly coupled to a thermal environment [7]. To account for the coupling energy, we have to analyze a thermodynamic cycle with four stages: the equilibrium storage stage is interrupted by disconnecting the system (a.k.a. battery) from the bath, then work is extracted from the battery, and then the battery is reconnected with the bath thermalizing. We study the case where the battery and charger together comprise a spin-1/2 Ising chain [8]. We show that the figures of merit—the extracted energy and the thermodynamic efficiency—can be enhanced by operating the cycle close to the quantum phase transition point.

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T04

Crafting Spin-Polarized Tunable Photocurrents in Topological Insulators

Harnessing topological materials for developing a new generation of topological-based devices is an unsolved challenge of great importance. Using Floquet scattering theory combined with tight-binding models of two-dimensional material with spin-orbit coupling, we study the interplay among laser illumination, spin, and topology. Starting from a topological phase, we show how laser illumination can selectively disrupt the topological edge states depending on their spin. This is manifested by the generation of pure spin photocurrents and spin-polarized charge photocurrents under linearly and circularly polarized laser illumination, respectively.

Quantum effects on current-driven nanodevices

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Nanoelectromechanical devices and molecular machines are topics that have attracted much attention in recent years [1, 2, 3]. The working principle of most of the studied systems relies on classical physics. However, for some devices, the quantum coherence length may be comparable to some of the system's dimensions, which could lead to new effects or even new working mechanisms. Here, we briefly review some of the recent works of our group about different nanodevices where quantum mechanics plays a central role. This includes different forms of quantum pumps and motors driven by voltage and temperature biases between the reservoirs that are connected to them. We aboard different nanodevices that only work in a quantum regime of the driving particles that flow between the reservoirs [4, 5, 6], discussing the true role of quantum mechanics in its driving mechanism and the effect of decoherence on them [6, 7, 8]. We also deal with some thermodynamic aspects of such systems including the possibility of using out-of-equilibrium reservoirs [9]. Finally, we tackle the possibility that current-induced forces (in a quantum regime of transport) play a significant role in some experimental examples [2] of molecular machines [10, 11].

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Copropagating edge states produced by the interaction between electrons and chiral phonons in two-dimensional materials

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Unlike the chirality of electrons, the intrinsic chirality of phonons has only surfaced in recent years [1]. In this talk, I will discuss on the effects of the interaction between electrons and chiral phonons in two-dimensional systems. In particular, I will show that chiral phonons induce inelastic Umklapp processes which produce copropagating edge states that coexist with a continuum. I will also show transport simulations to further reveal the robustness of these states against vacancy disorder [2]. Finally, I will discuss on the electronic interaction with two counter-propagating, chiral phonon modes, which leads to band gap openings and the emergence of blocking effects between valley, phonon mode and the direction of propagation of the resulting edge states.

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T07

Electronic transmission and its universal fluctuations in one-dimensional superlattices with Lévy-like disorder

We investigated the propagation of electronic waves in one-dimensional systems with Lévy-type disorder. We performed a complete analysis of non-relativistic and relativistic wave transmission submitted to potential barriers whose width, separation, or both follow Lévy distributions characterized by an exponent $0<\alpha<1$. For the first two cases, where one of the parameters is fixed, non-relativistic and relativistic waves present anomalous localization. However, for the latter case, in which both parameters follow a Lévy distribution, non-relativistic and relativistic waves present a transition between anomalous and standard localization as the incidence energy increases relative to the barrier height. Moreover, we obtained the localization diagram delimiting anomalous and standard localization regimes, in terms of incidence angle and energy. Finally, we verified that transmission fluctuations, characterized by its standard deviation, are universal, independent of barrier architecture, wave equation type, incidence energy, and angle, further extending earlier studies on electronic localization. Our predictions can be verified in graphene nanoribbons, where Dirac electrons are the main charge carriers. Most of the results have recently appeared in "Wave transmission and its universal fluctuations in quasi-one-dimension systems with Lévy-like disorder: Schrödinger, Klein-Gordon and Dirac equations", by A.L.R. Barbosa, J.R.F. Lima and L.F.C. PEREIRA in Physical Review E 106, 054127 (2022).

T08

Non-conservation of the valley density and its implications for the observation of the valley Hall effect

We show that the conservation of the valley density in a multi-valley insulator is broken in an unexpected way by an electric field, such as the one that is used to drive the valley Hall effect. This observation explains how a fully gapped insulator (i.e., one without edge states that cross the Fermi level) can support a valley Hall current in the bulk and yet show no valley density accumulation at the edges. If the insulator is not fully gapped, either because there are edge states crossing the Fermi level or because carriers are introduced in the conduction or valence band, then valley density accumulation at the edges is possible, paving the way to a direct observation of the valley Hall effect. However, the magnitude of the accumulation depends crucially on the inclusion of the anomalous electric field term in the continuity equation that relates valley current and density.

T09

Signatures of the order parameter of a superconducting adatom layer in quasiparticle interference patterns

Superconductivity has been observed in a 2D triangular lattice of Sn adatoms deposited on a Si (111) surface. As with any novel superconductor, identifying the symmetry of the superconducting order parameter is of the utmost importance, in order to shed light on the underlying pairing mechanism. To that end, we calculate the quasiparticle interference (QPI) patterns which would result from several putative order parameters, for scattering from charge disorder (impurities) and order parameter disorder (vortices). These patterns can be obtained experimentally as the Fourier transform of the real-space local density of states, measured by scanning tunneling spectroscopy. By performing the experiment in a varying magnetic field, the relative contributions to the QPI pattern from charge scattering and vortex scattering can be tuned. We show that characteristic differences between the charge and vortex scattering signals, at particular momentum transfers, can be used to distinguish between order parameters with different angular momenta.

T11

Electronic transport in Bi nanostructures through its hinge states

The electronic structure of Bi is topological and follows a generalized bulk–boundary correspondence of higher-order: the hinges of the material host topologically conducting modes. This affirmation is based on experimental detection of the hinge states [1] and analysis in the framework of Topological Quantum Chemistry [2] (based on Band Representation Theory) [3]. The hinge states provide intriguing features to the material. The approach of this project is calculating the electronic structure of Bi using the tight-binding Hamiltonian proposed in 2018 [2], which describes the topological states of the material. Then, electronic transport calculations were performed in KWANT [5] using two and three contacts in a nanostructure of Bi shaped as a hexagonal prism. This allows us to explore the transport through the hinge states and to induce interference between the states in the material. [1] Murani, Anil, et al. 2017. “Ballistic Edge States in Bismuth Nanowires Revealed by SQUID Interferometry.” Nature Communications 8 (July): 15941. [2] Schindler, Frank, et al. 2018. “Higher-Order Topology in Bismuth.” Nature Physics 14 (9): 918–24. [3] Bradlyn, Barry, et al. 2017. “Topological Quantum Chemistry.” Nature 547 (7663): 298–305. [4]Cano, Jennifer, and Barry Bradlyn. 2021. “Band Representations and Topological Quantum Chemistry.” Annual Review of Condensed Matter Physics 12 (1): 225–46. [5] Groth, Christoph W., Michael Wimmer, Anton R. Akhmerov, and Xavier Waintal. 2014. “Kwant: A Software Package for Quantum Transport.” New Journal of Physics 16 (6): 063065.

Steering the current flow in twisted bilayer graphene

T12

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A nanoelectronic device made of twisted bilayer graphene (TBLG) is proposed to steer the direction of the current flow, see Figure 1. The ballistic electron current, injected at one edge of the bottom layer, can be guided predominantly to one of the lateral edges of the top layer. The current is steered to the opposite lateral edge, if either the twist angle is reversed or the electrons are injected in the valence band instead of the conduction band, making it possible to control the current flow by electric gates. When both graphene layers are aligned, the current passes straight through the system without changing its initial direction. The observed steering angle exceeds well the twist angle and emerges for a broad range of experimentally accessible parameters leading to a non-local resistance, see Figure 2. It is explained by the trigonal shape of the energy bands beyond the van Hove singularity due to the Moiré interference pattern. As the shape of the energy bands depends on the valley degree of freedom, the steered current is valley polarized. Our findings show how to control and manipulate the current flow in TBLG. Technologically, they are of relevance for applications in twistronics and valleytronics.

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FIGURES

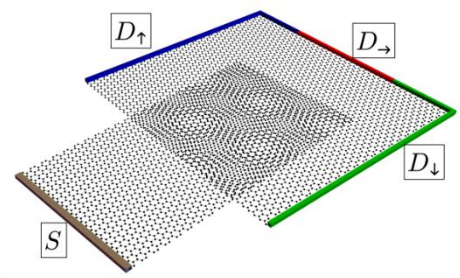

Figure 1: Schematic representation of the studied TBLG device. Electrons are injected through contact *S* at the bottom layer and detected by three drain contacts at the top layer.

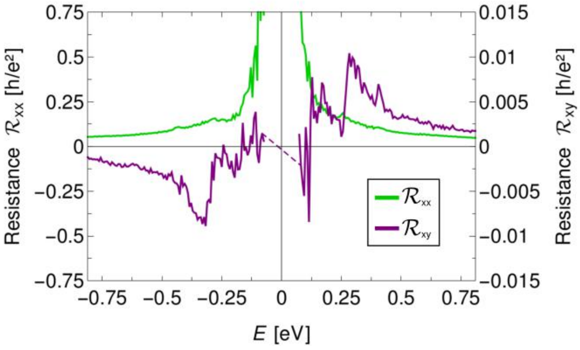

Figure 2: Longitudinal resistance R_{xx} and Hall Resistance R_{xy} as a function of energy for the TBLG device at a twist angle of θ=2.9°. The steering of the current flow to one of the lateral edges generates a non-local Hall resistance.

T13

Optical conductivity as a probe of the metal phase in rhombohedral trilayer graphene

Rhombohedral trilayer graphene (RTG) has been the focus of special interest in the last years, since it hosts a variety of phases. In particular the metallic phases give rise to exotic superconducting orders upon doping [H. Zhou et al, Nature 598, 429 (2021); ibid. 598, 434 (2021)]. In this work we study the optical conductivity using a continuum effective theory for three different proposed metallic ground states: a fully gapped valence-bond state, the bond-current state and the rotational symmetry breaking charge-density wave. We show that the optical conductivity presents characteristic features for each of the the metallic states and it can be used to distinguish between these different paramagnetic metallic ground states.

T14

Geometry dependence in hinges states in higher-order topological semimetals

The study of new topological states of matter is an important research topic in materials science. Knowledge about higher-order topological insulators (HOTIs) and higher-order topological semimetals (HOTSMs) have provided materials whose main characteristic is that they have gapless boundary states at lower dimensions [1]. In this work, we explore the role of geometry on the edge states in a higher-order topological semimetal constructed from the stacking of two-dimensional layers using the Kagome lattice with three-orbital tight-binding Hamiltonian [2] and we calculate the topological invariant using the non-abelian Berry phase. We analyzed three types of geometry of finite samples: triangular, hexagonal, and parallelogram, through their energy band dispersion and probability density. In the case of the hexagonal system, the localized states were found in three cross faces of the sample, unlike the triangular case, where the states are located on the hinges. This difference can be explained through the SSH model extension [3]. Finally, the conductance behavior is analyzed for these three electronic devices with two terminals, finding similarities for the three geometries. References [1] B. Xie, H.-X. Wang, X. Zhang, P. Zhan, J.-H. Jiang, M. Lu e Y. Chen. “Higher-order band topology.” Nature Reviews Physics, 3(7):520–532 (2021) DOI: 10.1038/s42254-021-00323-4. [2] H. Xue, Y. Yang, F. Gao, Y. Chong, and B. Zhang. “Acoustic higher-order topological insulator on a kagome lattice.” Nature Materials, 18(2):108-112 (2018) DOI: 10.1038/s41563-018-0251-x. [3] M. Ezawa “Higher-Order Topological Insulators and Semimetals on the Breathing Kagome and Pyrochlore Lattices.” Phys. Rev. Lett. 120, 026801 (2018). DOI: 10.1103/PhysRevLett.120.026801.

T15

Observing separate spin and charge Fermi seas in a strongly correlated one-dimensional conductor

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An electron is usually considered to have only one type of kinetic energy, but could it have more, for its spin and charge, or by exciting other electrons? In one-dimension (1D), the physics of interacting electrons is captured well at low energies by the linear Tomonaga-Luttinger Liquid (TLL) model, with hallmark predictions, such as spin-charge separation, having already been observed [1]. Recent theoretical work has focused on extending the theory to deal with more realistic curved dispersions [2, 3], however, little has been observed experimentally to date [4].

Here, we report on measurements of many-body modes in gated 1D wires connected via air-bridges [5] and using a momentum-resolved tunnelling spectroscopy technique based on resonant tunnelling between two nearby quantum wells. We map the 1D dispersion in a variety of devices, both in and out of equilibrium, and observe the formation of two separate Fermi seas at high energies, associated with spin and charge excitations, which cannot be accounted for by the non-interacting model [6]. We are able to control the electron density in the wires by tuning the level of confinement down to a density of about 18 electrons per micron. Similarly, by progressively occupying more 1D subbands we can change the amount of inter-subband screening by over 50%, consequently varying the effective interaction strength, *in situ*, all the way from the non-interacting limit $g = 1$ down to $g = 0.5$. Our spectroscopy technique offers an important tool for probing strongly correlated systems of varying interaction strength and dimensionality.

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T16

Spin hydrodynamics in antiferromagnetic insulators

Transport of spin and linear momentum in electrically insulating antiferromagnetic systems is investigated. We consider that low-energy spin-fluctuations, i.e., magnons, behave as a viscous fluid. This regime is set when momentum-relaxation length is below which the momentum-conserving scattering processes dominate. We study theoretically signatures from the hydrodynamic regime viscous effects, leading to a changes in transport measurements, such as nonlocal resistance measurements and in spin- and thermal-conductance transport experiments. Taking into account momentum- and spin-relaxation processes, we derive the hydrodynamic equations (momentum and spin) for the magnon fluid. In particular, we find that collisions between antiferromagnetic magnons carrying opposite spin-angular momentum, affects the propagation of spin currents in the form of drag-type effects. Our work pave the way towards the observation of magnon-fluid dynamics and pose it as an attractive platform to study in antiferromagnetic materials.