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Emergent Topological Phenomena in Two-Dimensional Quantum Materials and Designer Heterostructures

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Abstract

Two-dimensional (2D) quantum materials, ranging from simple atomic layers to layered Host rich correlated electronic phenomena and synthetic degrees of freedom are found in van der Waals (vdW) materials. Combined with designer heterostructures, which retain monolayer properties, these capabilities make the topology of the bands accessible and allow the formation of exotic topological phases.

Emergent topological phases in 2D quantum materials include quantum spin Hall, quantum anomalous Hall, Chern insulator and Dirac/Weyl semimetal phases. Topology is further engineered in designer heterostructures, moiré patterns, interlayer coupling, and external fields. The theoretical research into these phenomena has been expedited but the experiments are still scarce.

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1. Introduction

The recent development of the concept of two-dimensional (2D) quantum materials has not only revitalized the disciplines of condensed matter physics and materials science but also provided a vast amount of novel physics in comparatively largely understudied classes of emergent topological phases. These intriguing materials provide the new possibilities of studying 2D systems aimed at examining new emergent topological states based on the basic band topology and the typical exotic symmetry protection. Recent theoretical and experimental work in this field has described a range of new methods towards exploring different classes of emergent topological phases, which go beyond the constraints of first-generation topology, namely on the 2D limit. This effort includes the extra complications of many-body interactions, disorder, and in-layer coupling effects that arise under various interactions conditions, and which appear when these materials are contrasted with their more traditional three-dimensional equivalents. Besides taking advantage of the intrinsic properties such remarkable materials possess, a second key paradigm emerges which is the systematic stacking of layers in the process of designing interlayer interactions through the approach of van der Waals heterostructuring. This is an innovative method that builds up higher 2D quantum systems, which allow researchers to access outstanding stacking-induced emergent topological effects that are otherwise not accessible in single materials or when using other dimensions. This development is essential in the improvement of our comprehension of these multifaceted systems and their potential as a future technology [1, 2].

2. Essentials of Two-Dimensional Quantum Materials.

Two-dimensional (2D) quantum materials have rich physics because they have long Bloch-wave functions and a variety of band-structure properties. Efforts on such materials have been booming with the discovery of monolayer graphene. Graphene has negligible spin- orb cou- p8d32b663-2dce-439c-9dcf-6978ea0da409g (SOC) and does not have any topological phenomena other than the quantum Hall (QH) effect. Other intrinsic SOC 2D materials, including transition-metal dichalcogenides (TMDs), have been found as potential 2D topological insulators (TIs). Topological states and novel topological phases of stacked TMDs caused by proximity have been also predicted to occur in graphene/TMD heterostructures. A 2D Chern insulator candidate has been discovered to be bismuthene on an appropriate substrate, and can exhibit Chern insulator behavior. Stacks can also be formed of layered materials, including TMDs, magnetic van der Waals materials and 2D topological insulator materials. This opening up has the potential to create moiré patterns and novel flat-band physics, make it possible to realize unconventional topological superconductors and correlated states. In 2D materials or predicted in stacked structures, different phenomena have been observed, including quantum spin Hall (QSH) effect, quantum anomalous Hall (QAH) effect, and Weyl topology [1, 3].

2.1. Berry curvature and band topology.

The periodicity of the lattice is a conventionally used characterization to define the electronic states of solids in terms of Bloch bands. This gives the eigenstates of the single-particle Hamiltonian the potential to be associated with a geometrical structure with which the structure has been studied over decades [4]. Berry connection A geometric potential is a potential that may be built in the parameter space of problem Hamiltonians that satisfy some conditions [5]. Berry connections are used to compute the wave function change in the adiabatic transformations, and this result in an emergent phase factor, Berry phase, which adds to a variety of observable properties.

Such a comparison between the AharonovBohm and the Berry phase hints at defining an electromagnetic field as geometric, i.e. the Berry curvature of a Bloch band. The third band can be filled, unlike more traditional assumptions, by edge or surface states which satisfy a Dirac equation, and are closely related to the topology of the band structure. The fact that the band structure can be wrapped up into three-dimensional space gives rise to the concept of the Chern number, which is a topological invariant clearly only dependent on the form of a occupied Fermi surface and not affected by smooth deformations [6, 7, 8, 9].

2.2. Topological invariants and symmetry protections.

The existence of nontrivial bands with strong edge states may be of importance in exploring new uses of topology. In 2D band topology, a number of global topological invariants are characterised by parity eigenvalues of high-symmetry points, and topological invariants associated with mirror symmetry and rotation symmetry; in the absence of any symmetry, Chern topology may occur. Such invariants can be manipulated by interlayer coupling and proximity effects, and this enables the design of new topological phases.

The harsh confinement of two-dimensional materials increases the importance of topology since this significantly diminishes the number of permissible bulk states and in the process forms more comprehensive and richer edge states. The tight binding and lattice models are equivalent to effective two-dimensional continuum models, which corresponds to the KohnLuttinger model of the atomic orbitals that identifies material properties and makes use of the crystal symmetry of the two-dimensional Brillouin zone to identify distinct topological phases.

The noninteracting electronic states are either restricted by relations between the form of the Hamiltonian at various high-symmetry points, or by the geometry of the Brillouin-zone. Crystallographic symmetries like the \cal C 3 symmetry of twisted bilayer graphene can thus be due to three dimensional Dirac multiply degenerate states at the KKK + KK + and Gamma points. Symmetries between energy bands make it possible to map the two-dimensional semimetal on the surface to the three-dimensional one [10].

2.3. Proximity effects and interlayer coupling

Interlayer coupling is a crucial factor in multilayer two-dimensional (2D) materials and van der Waals heterostructures prepared of 2D quantum materials. With an increasing number of layers, interlayer hopping and hybridization are comparable, as well as the size of the orbital overlap, to the bandwidth of a single layer. The fact that interlayer coupling has a direct effect on the low-energy excitation spectrum means that the resulting phenomena are rich and diverse. Specifically, nontrivial topological bandgap 2D quantum materials are predicted to introduce new multilayers and heterostructures topology.

The resultant 2D bulk topological band structure that is induced by coupling to a topological insulator (TI) is the subject of strong research interest [11]. The recent theoretical studies also indicate that band topology of two 2D TIs could be either trivial, Z2, or Chern related to lattice symmetries and inherent spin-orbit interaction [12]. The mechanism of the hybridization-induced opening and closing of the gap is explained as well as the role of the crystal symmetry in safeguarding the topological invariants. The possibility of coupling a topological and a trivial layer provides an avenue of testing the flipping of the topological invariants that are brought about by hybridization in multilayered structures or hetero-structures [13].

3. Emergent Topological Phases in Two Dimensions.

Topological phenomena need three spatial dimensions, at least three-dimensional (3D). Even in a 2D system, such as the confinement of topological materials on the z axis (e.g. entrapment of electrons), the Hamiltonian may retain the topological properties on the 3D crystal scale, provided that the crystal symmetry is maintains. This can occur safely in a type-II van der Waals material, where non-Zero Chern number non-edge states are seen in 2D systems. Theoretically, 2D systems have been reported to have emerging topological phases, such as Quantum Spin Hall (QSH), Quantum Anomalous Hall (QAH), Chern and Z2 Topological Insulators (TI) and topological semimetals. Chiral mode dissipationless chiral modes are present in 2D in QSH and QAH, whereas 2D topological van der Waals materials such as CrX3 (X: I, Br, Cl) and at vertical single-layer (SL) or few-layer hetero-structures such as Graphene-WSe2.

The QSH phenomenon is described as the spin gapless insulating phase of a 2D hexagonal or square lattice, typically with the Chern number C = 0, with edge states crossing the bulk band gap. The QAH effect occurs in a system where the Chern number of magnetic order is non-zero. The QSH and QAH phases are both achievable in 2D transition metal dichalcogenide (TMD) CrX3 (X=I, Br, Cl) with a large band gap of more than 1 eV [15]. At the mono-layer level, the topology is prohibited but at the bi-layer stacking level, the topology is triggered by the joint protection of inversion symmetry and time-reversal symmetry at the stacking angle 0 o. The first-principles calculation of a minimal model of CrI3 indicates the stacking dependence and barrierless transition in bulk between QSH and QAH in CrBr3 instead of in-situ magnetic evolution system which remains a challenge when characterizing the sample [16]. The QAT stage has a distorted square or a hexagonal lattice structure with tetragonal or hexagonal magnetization. Therefore, both QSH and QAH phase hopping in a bi-layer structure is accessible in the 52 TMDs in the set of 8 that can be multi-stacked on top of each other at 0oC, with either CrI3, CrBr3, or CrCl3 to satisfy the C3 -regime. 2D Chern and Z2 topology at zero degrees Celsius with both multi-stacked growth and low energy-hermitian and Kzp-schematic modulations. Both experimentally and theoretically, Z2 and Chern topological phases have been found in a range of TMDs van-der-waal hetero-structures.

3.1. Quantum anomalous Hall and quantum spin Hall effects.

The quantum spin Hall (QSH) and quantum anomalous Hall (QAH) effects are two pillars of the topological transport phenomenon in two dimensions. These time-reversal symmetries (TRS)-making and TRS-breaking magnetism phenomena are respectively necessitated by 2D topological insulating systems called QSH and QAH insulators. The dissipationless spin-polarized current lies on the edge states of a QSH insulator, and an effective spin-filtering mechanism is possible. In spontaneously TRS breaking QAH insulator, integer quantized conductivity anomalous Hall is predicted. Although this has been theorized long since, it was not until quite recently that quantitative studies, which are smoke-free, were made a reality.

It was predicted that the QSH effect would be observed in graphene, which is a massless Dirac system, in the presence of spin-orbit coupling (SOC) that could be obtained through chemical functionalization or through Chern-Simons flux [17]. It has been since added to the already existing body of literature (theoretical and experimental) examining QSH and QAH in higher-order systems. It was proposed that the QAH effect would occur in ferromagnetically doped topological insulators, including (Hg,Mn)Te, and it was experimentally confirmed, as described in the following subsection. The QSH effect is the most technologically available emergent 2D QI structure transport phenomenon. The currently proposed candidate systems in providing the spin-filtering edge-state physics requirement seem to be the quasi-2D quantum-well systems of interest [18].

3.2. Chern and Z2 topological insulators in van der Waals materials

Topological insulators have been first defined in three dimensional systems. However, they have come into being, miraculously, as safeguarded states at the periphery, surfaces or interfaces of two-dimensional systems. This effect is seen when 2D-Chern insulator and quantum spin Hall insulator (QSHI) are implemented into 2D quantum van der Waals materials as independent or stacked or a spin-orbit coupled material of the two systems. Z2 topological materials where the topological invariant is the Z2 number and topological materials characterized by the Chern number are two important classes to date. The quantum-spin Halls (QSH) stacking of two-dimensional materials consisting of BiTeC, the Berry curvature responsibilities are defined on the basis of the edge states and energy spectrum of the 2D-driven topological insulators [19]. They show the Z2 topological insulators through stacking of van der Waals quantum materials by combining QSH and a Chern insulator simultaneously.

Theoretically, the first Chern insulators were introduced by Haldane in 1988, who supported an integer Hall effect without a net magnetic field whose topological index is the Chern number. The existence of nan-zero Chern number phases leads to quantized edges conductance. A Chern insulator, together with its time-reversal counterpart, creates a quantum spin Hall (QSH) insulator, which carries a less obvious topological number, the ℤ2 index, a topological invariant, showing trivial or nontrivial phases. Quantum wells of HgTe/CdTe and Bi2Se3 are 2D4-band Chern insulators with two counter-propagating spin-polarized edge states and break up the two original spin-degenerate bands into two pairs of spin-polarized edge states with a zero Chern number and retaining the Hamiltonian symmetry further. Chern-number band topology is a major subfield of topological-insulator physics that is actively being studied. Multi-component band model Hamiltonians can also be designed using geometrical ideas to create large Chern-number states as a topological-system platform of significant strength [20].

3.3. Semimetals in two dimensions Topologically in two dimensions.

Two-dimensional topological semimetals have other quantum properties that three-dimensional systems cannot have. Nontrivially topological systems indicate the existence of gapless surface states that backscattering and hybridization cannot form due to symmetry. Weyl and Dirac semimetals are semi-infinite 3D topological insulators, 3D nodal-line and higher-order systems that can not feature 2D projections in fully isolated structures. Theoretical and experimental studies of 2D topological semimetals indicate topological Dirac, Weyl, and nodal-line type states [21].

Early studies on 2D topological semimetals demonstrate that one can achieve topological characteristics that are not present in the 3D representation. The space group Pnma contains a two dimensional topological nodal-line phase that is crystalline symmetry-protected in monolayers. It has been anticipated that a nontrivial topology could be realized in 2D Hilton materials by this observation, Weyl - and nodal-line semimetals could provide a universal platform to control dimensions of surface states. The effects of hybridization are still important to consider in surface-state in the 3D to 2D transition.

4. Engineering of Topology and Designer Heterostructures.

The heterostructures formed by a combination of two-dimensional quantum materials and stacking sequences that are designed in a wide range offer access to new moiré superlattices that significantly expand the repertoire of electronic properties. Architected materials have emergent band gaps, flat bands, and band topology without having to substitute with chemical [1]. These additional degrees of freedom permit many-body phases, such as superconductivity, correlated insulators, and magnetism; as well as permit the topological and spin properties of the constituent layers to be protected [22]. The variants of stacking give different interlayer couplings and may provide a hybridization gap resulting in interface mediated topological states. Bilayer and trilayer configurations are tunable, and therefore, the experiment studies the strengths of layer-specific coupling and proximity-induced gap engineering on an experimental level.

Besides stacking, phase transitions and varying the set of preserved invariants in transition metal dichalcogenides intercalated with alkali metals can occur as a result of control parameters like strain, twist angles and vertical electric fields. A series of moiré bands would be available at certain angles together with an extra layer of symmetry and could facilitate both flat moiré bands and a second topological transition. To tune the gap in twisted bilayer graphene and other materials, there are various experimental knobs which can tune the gap without loss of flatness or moiré description, suggesting swaps between the trivial and Chern phases.

4.1. Piling up sequences and moiré superlattices.

The van der Waals heterostructures are called moire superlattices formed when two two-dimensional materials of dissimilar periodicities are overlaid. Recently these structures have drawn a lot of interest in order to allow the engineering of flat bands and other correlated states of matter [23]. Tucker *et al*. discover a novel process by which moiré superlattices can form in bilayers of transition metal dichalcogenides to produce emergent topology with only a small energy gap between high-symmetry stacking states. The authors construct a tight-binding model of multilayers of MoTe2 and WTe2, based on first-principles, in which topological properties of the system are further increased by the sequence of stacking [24].

4.2. Topological states that are interface-driven.

Interfacial states occur at the edge of 2D topological insulators, Dirac/Weyl semimetals and neighboring band insulators. These hybridized forms have gap opening as a result of the establishing the interfacial setup. In 0D systems, 0D states can be observed when the neighboring material is of trivial band topology and in 2D systems, a transition to a different crystalline symmetry can be observed to result in the appearance of symmetry-protected first-order topological insulators. Theoretical accounts have recently suggested the creation of interfacial states; the 0D modes that are topologically trivial or the 2D modes that are symmetry-protected at the interface of 2D materials with different topological invariants or different crystalline symmetries. Knowledge of the interplay between band topology and crystalline symmetry at the heterointerfaces of 2D materials provides the tunable design of these interfacial and bulk states, which is a convenient path to engineering topological properties [25, 26, 27, 28].

4.3. Strain, twist angles, and external fields as control parameters

Strain, twist angles and external fields can be used to continuously modulate material properties. Graphene has the highest relative strain tolerance [29] and therefore is a good candidate to strain engineering, which could cause quantum phase transition between a Dirac semimetal and an incoherent pseudogapped metal or a correlated insulator. These transitions create critical singularities in the thermodynamic response functions as nematic susceptibility separates. With sufficiently strong strain, a dimerized two-dimensional spin-singlet insulating state will form; a spin-charge-separated metallic phase can subsequently be doped to unconventional superconductivity. The deformation of graphene, therefore, changes the electronic structure substantially, providing an avenue to the vertex-mediated metal phase of quantum criticality.

The wide tunability of the moiré and interaction-driven effects of van der Waals heterostructure of transition metal dichalcogenides encourages the exploration of twisted bilayers outside of these materials. The Chern number of a twisted bilayer is a periodic function of the twist angle with a topological transition between C = 0 and C 1 at a number of combinations of the two-dimensional materials. This transition could also enable the change in the Zak phase and associated edge-state localization in the event where a layer of WSe 2 is twisted with respect to the next layer of graphene [13]. The topology in twisted bilayers may also be changed by external electromagnetic fields. The Chern number and energy of the different edge-states are changed by the addition of orbital magnetic fields, for example.

5. Representation of Realizations and Characterization Techniques through Experimentation.

Determining the appropriate materials and defining the topological states that they form is a significant objective in the study of emergent topological states in two-dimensional (2D) quantum materials and designer heterostructures. Other spectroscopic techniques that are directly topology-related, including angle-resolved photoemission spectroscopy (ARPES) and scanning tunneling microscopy (STM), provide a potent instrument in the momentum-resolved measurements of band structures. Other less sensitive methods to topological signatures have also been used to experimentally identify materials and structures which are topologically nontrivial phases. To give an example, bulk insulating systems with quantum spin Hall (QSH) or quantum anomalous Hall (QAH) states have been described by a combination of transport, spectroscopic and imaging methods [30]. Mesoscopic devices have been used to observe the helical edge modes in bilayer graphene/WSe2 heterostructures [31]. Signatures of low-energy effective models are available even in architectures that have not been completely described as topological, through transport measurements, and parameter control, including twist angle and external electric fields, further allows phase diagrams and phase transitions to be explored using experiments [32].

In the angle-resolved photoemission spectroscopy (ARPES), occupied single-particle energy eigenstates are obtainable by emitting photoelectrons off solid materials irradiated with suitable incident light. A variation in the incident photon energy can be used to probe the 2D band structure of the material and the kinetic energy and the angle of emission of the electrons detected at the same time recorded. In the research of band topology, special attention is given to the valence band maximum and the conduction band minimum since these two values characterize the character of the existing low-energy excitations and, therefore, the topology of the Bloch bands. A direct band gap between occupied and unoccupied states at specific momenta, which can still be accompanied by drastic transitions in the effective topological properties of the surface states, is an indication of the presence of bulk topological insulator phases.

5.1. Topological spectroscopic probes.

In order to detect the topological orders in 2D materials, spectroscopic probes are required to characterize spectroscopic signatures and selective edge-state excitations. It has been applied to angle-resolved photoemission spectroscopy (ARPES), scanning tunneling microscopy/scanning tunneling spectroscopy (STM/STS) and non-linear optical methods. There are quite remarkable differences between spectral fingerprints of various topologies. As an example, topologically protected edge states have been clearly demonstrated in 2D Chern insolators [33]. Monolayer (ML) and bilayer (BL) 2D WTe2 systems have been demonstrated to have quantum-spin-Hall (QSH) insulating states, with the bulk excitation gap robust to spin -orbit-coupling, as well as lattice-deformation perturbations, across the MLBL interface. Not only are strain-induced and external-gate-controlled phase transitions in QSH insulators exciting, but both are also thrilling in theory and experiment [34]. Bilayer systems can also have topological insulators with odd Z2 invariant. The helical edge states of the QSH insulator in BL WTe2 can be completely bubbled out by an in-plane magnetic field or by a perpendicular electric field and the transition can be made to a usual topological-insulator phase with an odd Z2 invariant. The experimental findings show that helical edge mode is non-reciprocal in the BL QSH insulator. A dual-topological-insulator environment has a stage where a topological Mott insulator occurs concurrently [35].

5.2. Quantized responses and transport signatures.

Another tool used in the study of topological states is the recurring use of either perpendicular or in-plane magnetic field, which experimentally implements systems with varying topological invariants and allows the phase diagrams of otherwise inaccessible systems to be explored [35]. Quantized response of a longitudinal d.c. potential has been predicted in a series of acidic and non-hydrogen-based acids, in the quantum Hall regime, as possible Chern insulators. The mapping of trivial and topological regimes over hall bars consisting of edge and bulk state contributions to the d.c. response has had complementary evidence offered by diagrammatic Monte Carlo techniques [36]. In the case of proximitely coupled monolayers, the coupleing between the layers is done by out-of-plane staggered E fields, achieved by vertically stacking the heterostructure. An orthogonal tight-binding model and low-energy effective theories have been introduced to justify the accrual of topological invariants, which are consistent with the periodic table of Chern insulators. On-site energy difference, tunnelling amplitude, staggered-inter-layer, electric field strength, and perpendicular magnetic fields on Chern insulators are adjustable perturbations that can be used to inform the choice of Chern insulated material to use in dispersion engineering [14].

5.3. Imaging and imaging-based evidence of edge and surface states

Two-dimensional (2D) topological insulator systems have been found to possess edge states from real-space measurements. These states are created around crystalline step edges, where environment changes locally induce hybridization of inter-edge states even with the characteristic Kramers spin-texture. Exceptional compatibility with a system WTe2 is a topological semimetal, which allows a large topological edge state at its step edges [37]. Investigations of Spectroscopic Imaging Scanning Tunneling Microscopy (SI-STM) at WTe2 step edges confirm the topological and trivial edge states, which provide the prospects of band-gap control, state confinement, and all-electrical energy-transition separation.

This quantum confinement is due to the fact that 2D materials have a multilayer structure and their density of states at the edges is increased by the number of layers less than that of the bulk. Other experiments have been aiming at deforming and controlling width of 2D materials to further modify edge-states. The 2D insulators have been probed [34], offering significant understanding of the interdependence of the bulk and edge states. The 2D materials also are welcoming to the moiré-superlattice assembly with hBN, giving the knobs of tuning to investigate the robustness of edge states. Formation of giant superlattice is permitted by stacking degrees of freedom together with long-range intermolecular interactions.

6. Computational Methods and theoretical Frameworks.

Topological insulators are bulk insulators that have conducting states at their surfaces or edges. These surface states are due to the topologicality of the band structure, and are resistant to perturbation. They are in two dimensions, and divided into Z 2 and Chern insulators, based on the presence of time-reversal symmetry. Topological insulators Topological insulators in two dimensions (2D) are thus appealing systems on which to implement exotic physics, and can be incorporated into van der Waals (vdW) heterostructures. The specifics of such systems are still obscure even as the 2D topological insulators have proliferated at a very high rate. The additional development of correlated TIs, further, makes the theoretical situation more complicated; correlation and topology interact to create exotic emergent phases and materials realization becomes of utmost importance [1].

6.1. Tight-binding models and effective field theories.

The collective excitations and emergent behavior of quantum materials is defined as a result of their ground-state many-body wave functions. Quantum materials have their many-body wave functions of their own, and enable the remarkable construction of tight-binding Hamiltonians that emulate the many-body formalism used in systematic companion methods. The formalism of many-body quantum materials used edget states in an alternative meaning, that is, in time-reversal- invariant and quantum-Hall states, but as a new family derived out of interaction effects. The continuous variable was also added in order to isolate different families, as it was demonstrated that related many-body Hamiltonians could make whole new material families vibrate. Even the time-reversal-invariant family, which is understood together with symmetry protection, displayed simultaneous phases of antagonistic nature underlying a new-interesting robustness and sign-change phenomenon [38, 39, 40, 41].

6.2. first-principles methods and more.

Topological Phenomena in Two Dimensional Quantum Materials and Designer Heterostructures.

Topological phases of matter can be manifested and studied using materials obtained as low-dimensional quantum systems. Low space dimensionality allows directions to the achievement of elusive topological phases, revealing new phenomena, which are inaccessible, in general, in three-dimensional topological systems. Topological materials This field has grown radically, with the identification of a variety of classes of topological materials that are not based on the three paradigms of bulk insulator, semi-metallic, and nodal-line materials, but on the class of two-dimensional systems. The investigation of more interesting features and functionalities with the help of ultra-thin materials will stay at the center of interest since two-dimensional quantum materials can be stacked into designer artificial systems whereby the interlayer couplings can be tuned. Stacking and twist angles also add additional richness to the material landscape, spawning a fertile landscape of theory-informed discovery of materials, phases and phenomena through predetermined prerequisites of low-energy effective models. Theoretical design principles are also applicable to chemically synthesized materials, where large scale first-principles modelling is parameterized by emergent phases driven by spin-oriented interactions, quadratic band-structure formation, and spin-orbit effects induced by vertex-coupling.

6.3. Topological diagnostics, numerical diagnostics.

The topological phases of quantum systems are specified by topological invariants. There are numerous numerical recipes to calculate these invariants in tight-binding Hamiltonians, and so two-dimensional topological states of matter have seen their classification [42]. Some examples are the Chern index of the integral of the Berry curvature over the Brillouin zone, the Z2 invariant of the parity of the occupied band eigenvalues of k points at time-reversal invariant momenta, and analogous invariants of mirror and rotation symmetry. More than discrete invariants, continuous quantities depending on gauge have been suggested to diagnose topology, including Wilson loops [43]. In the case of a topological insulator (heterostructure), a complementary measure of topology is the energy spectrum of edge states, and the topological phase diagram of such a material exhibits a different topological phase diagram in the particle-hole symmetric case.

7. Interaction with Correlations and Emergent Phenomena.

The focus of modern condensed-matter physics is on correlations and topology. The phenomena that can be studied using two-dimensional (2D) materials and moiré superlattices include Mott insulators, Wigner crystals, and stripe phases, which are all driven by correlations. Nevertheless, nontrivial band topology was not attained. AB-stacked heterobilayers MoTe2/WSe2 demonstrated a quantum anomalous Hall (QAH) effect, manipulated by out-of-plane electric field, which has a topological and bandwidth impact on the bands. At half-band filling, quantized Hall resistance and disappearance longitudinal resistance were seen at zero magnetic field. The topological phase transition between a Mott insulator and a QAH insulator due to the action of an electric-field is without a closing gap in bulk charge gap, and is followed by an insulator-to-metal transition. The present understanding of strong-correlation and topology emergent phenomena in moiré materials is promoted by this work [44].

Low-dimensional strongly correlated quantum systems frequently display exotic quantum ordering, through which it is only possible to see new forms of correlations. Such phenomena are such that new collective modes and fractional quantum numbers are generated. New orders caused by correlation are quantum spin chains and the quantum Hall effect [45].

7.1. Interaction-induced topological phases

Strong correlations among electrons can generate emergent topological states, dramatically enriching the known topological phase diagram. The topology of insulators, semimetals, and nodal superconductors may originate from band energetics, but such “band topology” remains an incomplete description for systems where correlations strongly renormalize or even completely alter the single-particle spectrum. Instead, even interacting systems with a purely particle-hole-symmetric spectrum can exhibit distinct topological behavior, where the wavefunction symmetry characterizing charge and spin density allows one to distinguish between trivial and nontrivial insulating states. Interaction-induced topological phases can be understood in terms of non-linear mean-field theories [46]. Following the established classification of non-interacting band topology for systems with spin-degenerate bands, bulk second-order topological phases [47] and higher-order topological phases possessing fragile topology remain to be explored. By treating interaction-induced symmetry breaking within the Hartree-Fock (H-F) approximation, the interplay between interactions and topological categorization has been investigated in twisted bilayer graphene [48].

7.2. Fractionalization in two-dimensional systems

In two-dimensional systems with nontrivial band topology, fractionalization compatible with time-reversal symmetry can give rise to space-time symmetric excitations with fractional braiding statistics. Several proposals explore the possibility of fractional Chern insulators relying on bosonic or fermionic atoms trapped in optical lattices, hybrid Chern insulators in coupled quantum-dot light-emitting diodes supporting fractional excitons and fractional spinor states, or quantum spin-Hall-like systems supporting Friedel oscillations and anyonic exchanges that interpolate between fractional quantum Hall states. Various mean-field and beyond-mean-field approaches, generally applied to higher-dimensional systems, suggest that single-layer and bilayer moiré systems may host projected fractional Chern and quantum Hall states, while interacting multi-layer systems dynamically select among competing fractional states [49, 50].

7.3. Disorder, localization, and robustness of topological states

Impurities, disorder, and finite-size effects can destroy the signature insulating properties of two-dimensional quantum Hall systems. On large scales, the mobility gap of a disordered two-dimensional band structure usually tends to the smallest energy scale of the problem. When the size of a Hall bar shrinks, instantaneous interference between all paths connecting the two contacts induces a delocalization of the electron wave function across the Hall-bar width of such strength that the states no longer form a well-defined edge state. Various arguments and analogous results in d > 2 raise the question of whether such results carry over to topologically-protected states in finite-size two-dimensional quantum Hall systems. It is therefore of interest to investigate the interplay between disorder and these states of such small spatial extension and of such a long-lived nature.

Systematic studies in a minimal model of a two-dimensional Chern insulator find that the energy difference between the Chern insulator state and the state with the opposite Chern number, the critical energy, remains almost constant under the effect of disorder. More than two-thirds of the original gap survive in the presence of very strong disorder. Any breakdown appears at much larger disorder strength than that needed to destroy transport properties; strong localization protects the edge channels from localization and background potential fluctuations, which create a tendency for localization to occur symmetrically around the two edges of the Hall-bar geometry. Such energies are fully delocalized across the width of the Hall bar [51, 52, 53].

8. Applications and Outlook

Emergent Topological Phenomena in Two-Dimensional Quantum Materials and Designer Heterostructures: Applications and Outlook

Embeddable topological states, the very same electronic states responsible for features such as the quantum Hall effect, have hence already been analysed in two-dimensional systems, where such systems have been steadily growing in fashion and applications. Due to the nature of these designer structures and their layered material combinations, physics far beyond the standard models emerges and consequently, a host of disorder-driven and correlation-driven phenomena have been predicted.

Chirality in 2D, pivotal for the envisioned benefits of mobile charge being guarded by robust edge channels for spintronics and QIS applications, has been the focus of current attention: indeed, first-principles calculations highlighted its inherent correlation with orbital character rather than with the often-invoked Chern numbers. Nevertheless, engineering a full-fledged topologically nontrivial band structure beyond the standard 2D models seems out of reach. Heterostructures and multilayers enhance the breadth of 2D materials and permit the design of moiré superlattices or arbitrary band interleaving.

Numerous avenues remain open ranging from ever more complex interplay of symmetry, disorder, and interactions to the exploration of novel exotic topological phases, e.g., to mimic 2D fractional Chern insulators with anyonic excitations, interlayer excitons, or genuine topological superconductivity, raising the need for dedicated further investigations [54].

8.1. Quantum information and spintronics

Contemporary concepts of quantum information technology and spintronics leverage proximity and interlayer coupling between layers of 2D quantum materials that host a quantum spin Hall effect [55]. Proposals even posit the use of twisted bilayer graphene, which supports emergent phenomena that can influence and enhance superconductivity. These materials exhibit valley- and layer-dependent orbital magnetic moments within a double-quantum-dot configuration in nearby regions of the Brillouin zone, while the qubit state can be probed through charge detection from a nearby quantum dot [17].

8.2. Energy conversion and catalysis implications

A rich variety of two-dimensional (2D) materials and heterostructures emerge from van der Waals materials with tunable and programmable topology by exploiting the interlayer coupling in adjacent materials or the on-site diagonal perturbation in single-layer materials. Topological materials have garnered extensive attention owing to their exotic surface states [56]. Further, many-body correlated systems, exothermic electrochemical reactions, and mass-transport processes such as proton/electron transfers and phase conversions during energy storage or conversion play significant roles in catalysis and energy devices. Catalytic activity is intricately linked with charge transport and underlines the synergy between topology and electrocatalysis for energy-related devices and the intrinsic relationship between many-body correlated systems and emergent topological phases. Topological charge pumps are sources of charge, thermal, energy, or particle transport; hence, topological energy conversion becomes relevant to time-dependent driving forces in various systems.

8.3. Challenges, open questions, and future directions

Two-dimensional quantum materials and designer heterostructures supporting emergent topological phenomena have unfolded a wealth of artistic avenues. These include interaction-driven correlation effects in single- and bilayer systems, pursuit of higher-spin physics in two-dimensional magnets, topological excitations in quantum spin liquids, strain-induced effects, and quantum mechanics of two-dimensional water rings. The quest continues to capture multidimensional topological invariants beyond band topology preserving crystalline symmetries in hyperbolic 2-D materials. Coarse-grained, collective models guiding low-lying excitations within quantum Hall states and topology-driven phase locks integrating topological insulators and superconductors are emerging [1] to enter nonlinear regimes at strong coupling. Perturbation methods capturing, e.g., renormalization of gaps, and global codes enabling field- and topological-structure representations of Weyl nodes in real and reciprocal spaces are of interest [57]. Magnetic impurities enhancing lotka-volterra singlet dynamics and proximity-enhanced topological gaps close one of several open circuits in evolving time-scale models. Theoretical scenarios describing topological phases and supporting materials enabling observation of fractional Chern insulators require deeper exploration. Observing and controlling phase transitions from Chern to fractional states in ~10^18/m^2 layers furnishes guidance on temporally complicated quantum avalanches with vast-scale implications that challenge bounding descriptions.

Materials sustaining currents worthy of quantum transport follow in sneakers atop diverse substrates and across lengthscales compatible with dedicated architectures. So-called superlattices with unprecedentedly low twist angles between stacked transition-metal dichalcogenide couples, zoning rugged phase-space regions mapping magnetic-corral lattices, exhibit captivating physics extending beyond the zero-dimensional limit or into squeezed time-varying landscapes. Transport signatures linked to various topologies in probe-accessible locations with expected charge-carrier mobilities support uniformity across dozens of transitions.

9. Conclusion

On the whole, emergent topological phenomena in 2D quantum materials and designer heterostructures offer unprecedented opportunities to enrich the spectrum of topological states and to broaden the usability of topological concepts. A large variety of unique topological phases appears with minimal intervention in stacking sequences, lateral arrangements, or interlayer coupling, establishing a paradigm where topological properties are determined by design rather than by confinement, symmetry, or chemical composition, concepts usually associated with condensed matter physics. Alongside aforementioned phases with elementary topological properties, more exotic architectures are expected, including teleportation-based quasiparticle braiding, self-dual topological excitations of infinite order, and fractional generalizations of the 2D classical Ising universality class. Such structures could remain easily accessible with state-of-the-art fabrication technique.

The interplay between topology and correlations also emerges as a major theme. The combination of topological defects related to band topology and strong interactions may give rise to new forms of fractionalization beyond 1D, with potential realizations in the Moore–Read phase. Driven by the frontier of 2D materials and designer approaches, the exploration of topological phases transcends first two questions, aiming instead to uncover a complete landscape of achievable topological states and their interplay with correlations, gauge fields, and emergent symmetry.

10. References

1. Lado JL, Liljeroth P. Designer quantum matter in van der Waals heterostructures. *Not specified*. 2021.
2. Belopolski I. Discovery of magnetic topological crystals. *Not specified*. 2020.
3. Lin CY, Do TN, Wu JY, Shih PH, *et al*. Diverse quantization phenomena in layered materials. *Not specified*. 2019.
4. Cayssol J, Fuchs JN. Topological and geometrical aspects of band theory. *Not specified*. 2020.
5. Song JCW, Samutpraphoot P, Levitov LS. Topological Bloch bands in graphene superlattices. *Not specified*. 2015.
6. Ledwith PJ, Vishwanath A, Khalaf E. Family of ideal Chern flatbands with arbitrary Chern number in chiral twisted graphene multilayers. *Phys Rev Lett*. 2022.
7. Kruchkov A. Quantum geometry, flat Chern bands, and Wannier orbital quantization. *Phys Rev B*. 2022.
8. Cayssol J, Fuchs JN. Topological and geometrical aspects of band theory. *J Phys Mater*. 2021.
9. Liu GG, Gao Z, Wang Q, Xi X, Hu YH, Wang M, Liu C. Topological Chern vectors in three-dimensional photonic crystals. *Nature*. 2022.
10. Po HC, Vishwanath A, Watanabe H. Symmetry-based indicators of band topology in the 230 space groups. *Not specified*. 2017.
11. Hsieh TH, Ishizuka H, Balents L, Hughes TL. Bulk topological proximity effect. *Not specified*. 2015.
12. Zutic I, Matos-Abiague A, Scharf B, Dery H, *et al*. Proximitized materials. *Not specified*. 2018.
13. Pezo A, Zanolli Z, Wittemeier N, Ordejon P, *et al*. Manipulation of spin transport in graphene/transition metal dichalcogenide heterobilayers upon twisting. *Not specified*. 2020.
14. Cho GY, Moon EG. Novel quantum criticality in two dimensional topological phase transitions. *Not specified*. 2016.
15. Lau A. Symmetry-enriched topological states of matter in insulators and semimetals. *Not specified*. 2018.
16. Shavit G, Goldstein M. Topology by dissipation: Transport properties. *Not specified*. 2019.
17. Young AF, Sanchez-Yamagishi JD, Hunt B, Choi SH, *et al*. Tunable symmetry breaking and helical edge transport in a graphene quantum spin Hall state. *Nature*. 2014;505(7484):528-532.
18. Shamim S, Beugeling W, Böttcher J, Shekhar P, *et al*. Emergent quantum Hall effects below 50 mT in a two-dimensional topological insulator. *Sci Adv*. 2020;6(26):eaba4625.
19. Kou L, Wu SC, Felser C, Frauenheim T, *et al*. New family of robust 2D topological insulators in van der Waals heterostructures. *Not specified*. 2014.
20. Sticlet D, Piéchon F, Fuchs JN, Kalugin P, *et al*. Geometrical engineering of a two-bands Chern insulator in two dimensions with arbitrary topological index. *Not specified*. 2012.
21. Hu J, Xu SY, Ni N, Mao Z. Electronic transport and quantum oscillation of topological semimetals. *Not specified*. 2019.
22. Belopolski I, Xu SY, Koirala N, Liu C, *et al*. A novel artificial condensed matter lattice and a new platform for one-dimensional topological phases. *Sci Adv*. 2017;3(3):e1501692.
23. Tsai KT, Zhang X, Zhu Z, Luo Y, *et al*. Correlated insulating states and transport signature of superconductivity in twisted trilayer graphene moiré of moiré superlattices. *Phys Rev Lett*. 2021;127(16):166802.
24. Hart JL, Bhatt L, Zhu Y, Han MG, *et al*. Emergence of layer stacking disorder in c-axis confined $MoTe_2$. *Not specified*. 2022.
25. Ge Y, Shi B, Xia J, Sun H, Yuan S, Xue H. Programmable dual-band acoustic topological insulator with dynamically movable interface states. *Appl Phys Rev*. 2023;10(3):031403.
26. Liu F. Two-dimensional topological insulators: past, present and future. *Coshare Science*. 2023;01(03).
27. Liu J, Hesjedal T. Magnetic topological insulator heterostructures: A review. *Adv Mater*. 2023;35(27):e2102427.
28. Yi H, Zhao YF, Chan YT, Cai J, Mei R, Wu X, Yan ZJ. Interface-induced superconductivity in magnetic topological insulators. *Science*. 2024;383(6683):634-639.
29. Arya S, Laad MS, Hassan SR. Exploring novel quantum criticality in strained graphene. *Not specified*. 2016.
30. Lohse M, Schweizer C, Price HM, Zilberberg O, *et al*. Exploring 4D quantum Hall physics with a 2D topological charge pump. *Nature*. 2018;553(7686):55-58.
31. Tiwari P, Kumar Srivastav S, Ray S, Das T, *et al*. Observation of time-reversal invariant helical edge-modes in bilayer graphene/WSe_2 heterostructure. *ACS Nano*. 2021;15(1):916-922.

32. Liu JX, Wang JT, Ding HT. Detecting degenerate bands topological invariants in optical lattice. *Not specified*. 2024.
33. Goldman N, Dalibard J, Dauphin A, Gerbier F, *et al*. Direct imaging of topological edge states in cold-atom systems. *Proc Natl Acad Sci U S A*. 2013;110(17):6736-6741.
34. Xu SY, Neupane M, Belopolski I, Liu C, *et al*. Unconventional transformation of spin Dirac phase across a topological quantum phase transition. *Nat Commun*. 2015;6:6870.
35. Weisbrich H, Klees RL, Rastelli G, Belzig W. Second Chern number and non-Abelian Berry phase in topological superconducting systems. *PRX Quantum*. 2021;2(1):010310.
36. Swingle B. Experimental signatures of 3d fractional topological insulators. *Not specified*. 2012.
37. Peng L, Yuan Y, Li G, Yang X, *et al*. Observation of topological states residing at step edges of WTe_2. *Nat Commun*. 2017;8:659.
38. Yang CJ, Li J, Fiebig M, Pal S. Terahertz control of many-body dynamics in quantum materials. *Nat Rev Mater*. 2023;8(8):518-532.
39. Cotler JS, Mark DK, Huang HY, Hernández F, Choi J, *et al*. Emergent quantum state designs from individual many-body wave functions. *PRX Quantum*. 2023;4(1):010311.
40. Xu C, Zong A. Time-domain study of coupled collective excitations in quantum materials. *npj Quantum Mater*. 2025;10:21.
41. Nocerino E. Emergent properties and the multiscale characterization challenge in condensed matter, from crystals to complex materials: a review. *arXiv preprint arXiv:2503.20266*. 2025.
42. Wang Z, Zhang SC. Topological invariants and ground-state wave functions of topological insulators on a torus. *Phys Rev X*. 2014;4(1):011006.
43. Caio MD, Möller G, Cooper NR, Bhaseen MJ. Topological marker currents in Chern insulators. *Nat Phys*. 2019;15(3):257-261.
44. Li T, Jiang S, Shen B, Zhang Y, *et al*. Quantum anomalous Hall effect from intertwined moiré bands. *Nature*. 2021;600(7890):641-646.
45. Girvin SM. Exotic quantum order in low-dimensional systems. *Not specified*. 1997.
46. Wang C, Potter AC, Senthil T. Classification of interacting electronic topological insulators in three dimensions. *Science*. 2014;343(6171):629-631.
47. Julià-Farré S, Müller M, Lewenstein M, Dauphin A. Self-trapped polarons and topological defects in a topological Mott insulator. *Phys Rev Lett*. 2020;125(24):240601.
48. Kim J, Kim J, Kim KS, Jhi SH. Topological phase transition in Dirac fermionic heterostructures. *Not specified*. 2012.
49. Hou CY, Chamon C, Mudry C. Electron fractionalization in two-dimensional graphenelike structures. *Phys Rev Lett*. 2007;98(18):186809.
50. Meng T. Fractional topological phases in three-dimensional coupled-wire systems. *Phys Rev B*. 2015;92(11):115152.
51. Wang XS, Wang YJ. Disorder-order transition in multiprincipal element alloy: A free energy perspective. *Phys Rev Mater*. 2023;7(3):033606.
52. Zhu J, Wei M, Xu J, Yang R, Meng X, Zhang P. Influence of order-disorder transition on the mechanical and thermophysical properties of $A_2B_2O_7$ high-entropy ceramics. *J Adv Ceram*. 2022;11(8):1222-1234.
53. Chaudhuri D, Barbalas D, Romero R III, *et al*. Anomalous high-temperature THz nonlinearity in superconductors near the metal-insulator transition. *Not specified*. 2022.
54. Li Y, Xu Y. First-principles discovery of novel quantum physics and materials: From theory to experiment. *Comput Mater Sci*. 2021;188:110153.
55. Banerjee N, Bell C, Ciccarelli C, Hesjedal T, *et al*. Materials for quantum technologies: A roadmap for spin and topology. *Appl Phys Rev*. 2025;12(4):041328.
56. Peng Y, Refael G. Topological energy conversion through bulk or boundary of driven systems. *Not specified*. 2018.
57. Culcer D, Keser AC, Li Y, Tkachov G. Transport in two-dimensional topological materials: Recent developments in experiment and theory. *2D Mater*. 2020;7(2):022007.

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