

**QUANTUM MATERIALS: FUNDAMENTAL PHENOMENA, EXPERIMENTAL INSIGHTS,
AND EMERGING TECHNOLOGICAL APPLICATIONS***Branko MATOVIĆ^{1,*}, Emilija NIDŽOVIĆ¹*

¹ Center of Excellence “CEXTREME LAB”, Vinča Institute of Nuclear Sciences - National Institute of the Republic of Serbia, University of Belgrade, Belgrade, Serbia

*Corresponding author: mato@vinca.rs (Branko Matović)

Abstract: *Quantum materials have emerged at the forefront of contemporary research in solid-state chemistry, physics, and materials science, owing to their unique properties rooted in quantum mechanical phenomena such as coherence, entanglement, and topological protection. This diverse class of materials has immense potential to drive a new technological revolution, with applications ranging from quantum computing and sensing to energy harvesting and spintronics. This review offers a concise summary of the fundamental quantum effects that define these materials, highlights key experimental techniques used for their characterization, and discusses their potential for usage in next-generation technologies. Despite significant advances, notable challenges persist in the synthesis, theoretical modeling, and integration of quantum materials into functional devices. Future research holds a promise for new discoveries, paving the way for novel applications and a deeper understanding of the quantum nature of matter.*

Keywords: Quantum Materials; Quantum Computing; Superconductivity; Topological Phases; Strongly Correlated Electron Systems

1. Introduction

Quantum materials represent a distinct class of materials whose properties are defined by quantum mechanical effects that transcend the explanatory scope of classical physics. This diverse group includes superconductors (Figure 1-3), topological materials, quantum spin systems, and other compounds whose behavior cannot be predicted or explained by analyzing individual particles, as it emerges as a result of collective behavior in many-particle systems. Research in quantum materials has not only deepened our fundamental understanding of condensed matter systems but has also initiated technological advances in fields such as quantum computing, quantum communication, and superconducting electronic devices.

The conceptual foundations of quantum materials originate from the development of quantum mechanics in the early twentieth century, marked by the pioneering contributions of Max Planck, Albert Einstein, Niels Bohr, and Werner Heisenberg. While quantum mechanics was initially focused on the atomic and subatomic scale, it went on to provide a framework for understanding macroscopic quantum phenomena. One of the key milestones was the discovery of superconductivity by Heike Kamerlingh Onnes in 1911, who observed the complete disappearance of electrical resistance in mercury at cryogenic temperatures [1]. This phenomenon was later explained on a microscopic level using the BCS theory, developed in the 1950s and named after its authors - John Bardeen, Leon Cooper, and Robert Schrieffer, who introduced the concept of electrons pairing into a collective quantum state [2,3].

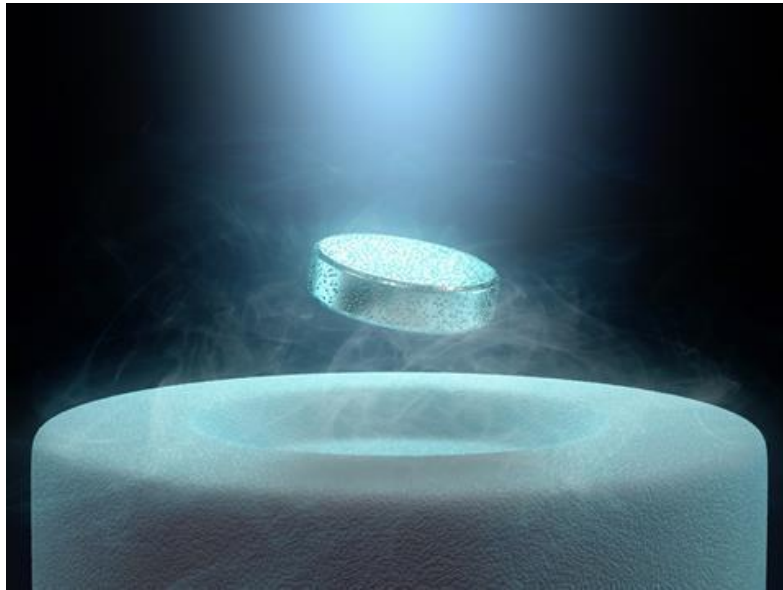


Figure 1. A magnet levitating above a high-temperature superconductor, cooled with liquid nitrogen.

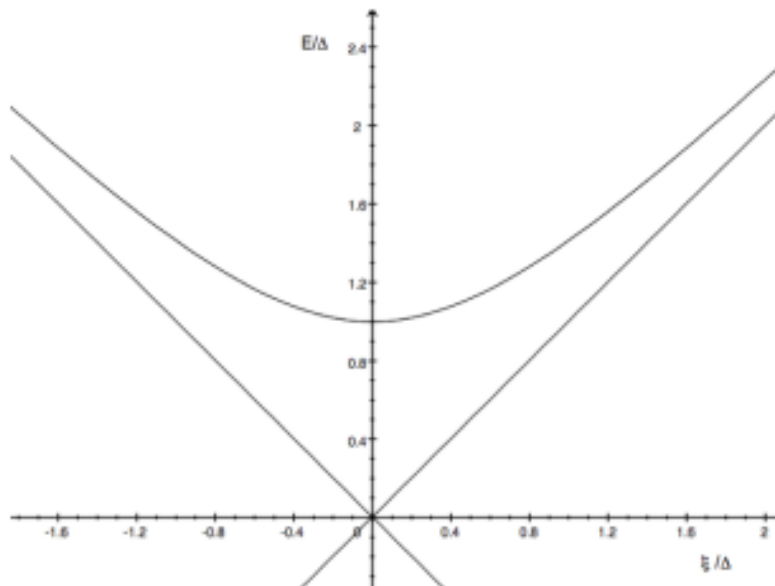


Figure 2. The energy gap seen between the superconducting state (top) and normal state (bottom) produces the order parameter of the system.

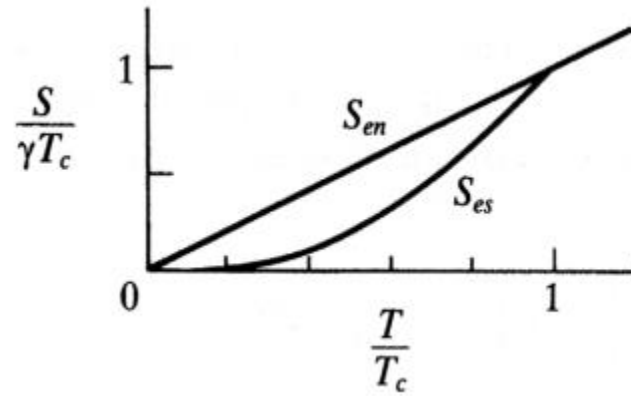


Figure 3. Comparing the entropy dependence on temperature: the superconducting state, S_{es} , is more ordered than the normal state S_{en} .

The 1980s and 1990s marked a pivotal period in the study of quantum materials, with the discovery of the quantum Hall effect (Figure 4) in two-dimensional electron systems [4], which prompted extensive theoretical and experimental research on the topological phases of matter [5,6]. These breakthroughs revealed the existence of quantum states that are robust against perturbations, even in the presence of defects and disorder. The subsequent discoveries of topological insulators and topological superconductors established a new paradigm in condensed matter physics and paved the way for applications in fault-tolerant quantum computing.

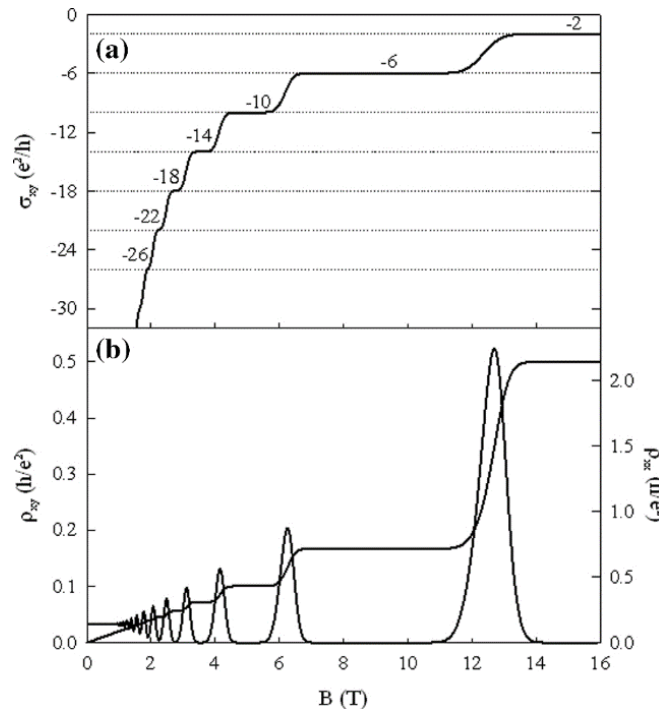


Figure 4. (a) Simulation in monolayer graphene of the Hall magnetoconductivity. (b) Hall diagonal magnetoresistivities, as a function of the magnetic field: The electron density at zero magnetic field used in the simulation was $n_0 = 6 \times 10^{15} \text{ m}^{-2}$ and a Gaussian width of $\Gamma = 0.025 \text{ eV}$ [7]

Entering the 21st century, the field was once again revolutionized with the isolation and characterization of two-dimensional materials, most notably graphene (Figure 5), whose exceptional mechanical,

electrical, and optical properties have warranted research on van der Waals layered materials and their quantum behavior [8]. Simultaneously, the controlled fabrication of nanostructures such as quantum dots, nanowires, and nanoparticles has enabled the manipulation of quantum effects at the nanoscale, accelerating the development of novel quantum devices.

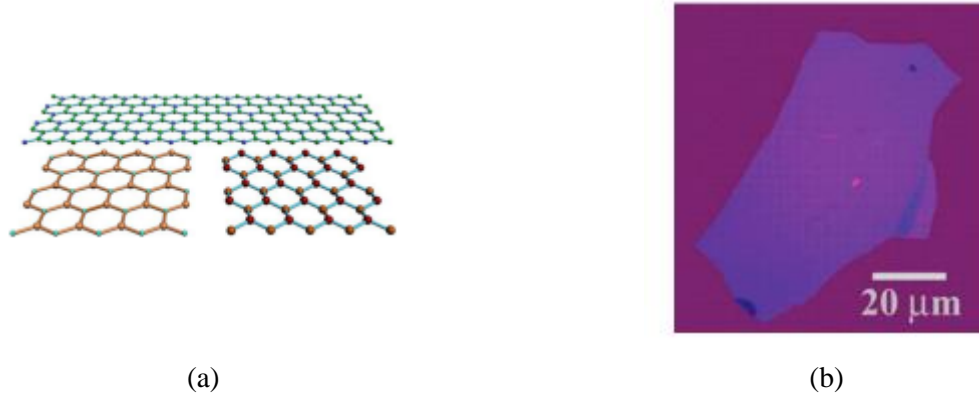


Figure 5. (a) Two-dimensional structure of graphene. (b) Micrograph of a large multilayer graphene flake with a thickness of ~ 3 nm on top of an oxidized Si wafer [9].

In recent years, the pursuit of scalable and efficient quantum computing has further encouraged interest in quantum materials, particularly those that support qubit implementation based on superconducting circuits, trapped ions, and topologically protected states. Such development paths highlight the key role of quantum materials in the evolution of information technology, advanced sensing, and communication networks.

Today, quantum materials are crucial for the progress of a wide range of scientific and engineering disciplines, including nanoelectronics, superconductivity, spintronics, topological quantum technologies, and quantum photonics. Understanding and engineering their properties remains a key challenge and opportunity for the development of next-generation technologies in quantum computing.

This review aims to provide a comprehensive outline of the historical development of quantum materials, emphasizing key milestones, current research directions, and the fundamental physical principles underlying their remarkable properties.

Table 1. Overview of key emergent quantum phenomena and the materials in which they arise.

Emergent quantum phenomenon	Description	Typical materials	Potential applications
Superconductivity	Disappearance of electrical resistance at low temperatures due to electron pairing (Cooper pairs)	Nb, YBa ₂ Cu ₃ O ₇ (YBCO), FeSe	Quantum computing, magnetic levitation, MRI
Topological Insulator	Materials that act as insulators in their interior with topologically protected conducting surface/edge states	Bi ₂ Se ₃ , Sb ₂ Te ₃ , HgTe quantum wells	Quantum computing (topological qubits), spintronics
Quantum Hall Effect	Quantized resistance observed in 2D electron systems under strong magnetic fields	GaAs/AlGaAs heterostructures	Resistance standards, precision metrology
Quantum spin liquid	A collective quantum state lacking long-range magnetic order, even at 0 K	Herbertsmithite ZnCu ₃ (OH) ₆ Cl ₂ , κ-(BEDT-TTF) ₂ Cu ₂ (CN) ₃	Quantum computing, quantum memory
Quantum phase transition	A phase transition occurring at zero temperature driven by quantum fluctuations	CeCu _{6-x} Au _x , Sr ₃ Ru ₂ O ₇	Unconventional quantum criticality
Majorana quasiparticles	Quasiparticles that are their own antiparticles, emerging in topological superconductors	InSb nanowires + NbTiN (in heterostructures)	Topological quantum computing

2. Historical Milestones in Quantum Materials Research

The history of quantum materials research is closely intertwined with the development of quantum mechanics and condensed matter physics. Several key discoveries made during the first half and mid-20th century laid the groundwork for what would later evolve into a rich and dynamic field focused on materials whose properties are fundamentally governed by quantum effects.

2.1. Early Quantum Discoveries in Condensed Matter Physics

One of the first major quantum phenomena observed in a material on a macroscopic scale was the discovery of superconductivity in 1911 by Heike Kamerlingh Onnes [1]. While investigating the electrical resistance of metals at cryogenic temperatures, Kamerlingh Onnes found that mercury exhibited zero electrical resistance below a critical temperature (approximately 4.2 K). This unexpected behavior indicated the presence of a collective quantum state, although a theoretical explanation would not emerge until several decades later. Superconductivity remains one of the most prominent examples of macroscopic quantum coherence.

Another landmark discovery occurred in 1980, when Klaus von Klitzing observed the phenomenon now known as the quantum Hall effect [10]. In a two-dimensional electron gas subjected to a strong magnetic field, he found that the Hall resistance becomes precisely quantized in integer multiples of fundamental physical constants. This occurrence, which cannot be explained by classical electromagnetism, demonstrated that quantum mechanics can govern the collective behavior of electrons in thin layers of materials. The quantum Hall effect also paved the way for new concepts such as topological order - a different framework for understanding phases of matter that goes beyond the traditional symmetry-breaking theory. These early discoveries have shown that quantum effects are not restricted to individual atoms or molecules, and can manifest themselves through collective properties of solids, creating entirely new states of matter.

2.2. Theoretical Frameworks Development

Following significant experimental discoveries, new quantum theories of materials were developed to better understand the underlying phenomena. The BCS theory of superconductivity, formulated in 1957 [2,3], explained that electrons in superconductors form Cooper pairs via phonons, enabling resistance-free current flow. This theory laid the foundation for understanding other quantum collective phenomena.

Subsequently, the discovery of the quantum Hall effect led to the development of topological band theory [11], which introduced concepts such as topological invariants - robust system properties enabling edge/surface states resilient to defects. This theory laid the foundation for the discerning of topological insulators, superconductors, and Weyl semimetals.

The convergence of experimental and theoretical advances significantly transformed our understanding of phase transitions, symmetry, and quantum coherence, and initiated the quest for new quantum phases of matter.

3. Classes of Quantum Materials

Quantum materials encompass a diverse range of systems in which quantum mechanical effects have the dominant role, often giving rise to entirely new states of matter. They can be broadly categorized based on the main quantum phenomena they exhibit. In this section, several major classes of quantum materials that have gained considerable interest within the scientific community will be presented.

3.1. Superconductors

Superconductors are materials that, below a certain critical temperature (T_c), exhibit two key characteristics: complete absence of electrical resistance and the expulsion of magnetic field from their interior - a phenomenon known as the Meissner effect [12]. These properties stem from fundamental quantum mechanical principles and represent macroscopic quantum phenomena (Figure 6).

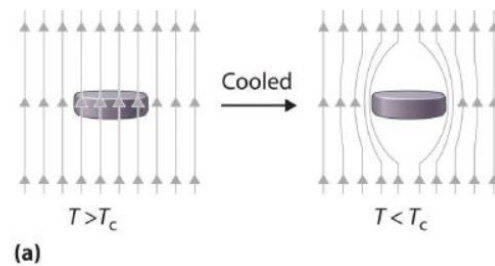


Figure 6. Meissner effect: (a) Below its critical temperature, a superconductor expels magnetic field lines. (b) A magnet levitates above a $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ disk cooled in liquid nitrogen.

In conventional superconductors, which include many metals and alloys (e.g., niobium and lead), superconductivity is explained by the Bardeen-Cooper-Schrieffer (BCS) theory. According to this theory, at low temperatures, electrons form so-called Cooper pairs due to attractive interactions mediated by phonons - collective lattice vibrations. These pairs condense into a joint quantum state that allows for resistance-free current flow without scattering [3].

However, at the end of the 20th century, a new class of materials was discovered - unconventional superconductors, including cuprates (copper-based oxides) and iron-based superconductors [13]. These materials are superconductive at much higher temperatures, often above 77 K (the boiling point of liquid nitrogen), which makes them interesting for technological applications [14]. In the case of these materials, the BCS theory is insufficient in explaining the pairing mechanisms [15]. It is considered that spin fluctuations, orbital instabilities, or exotic quantum excitations may mediate pairing instead of phonons [16].

Unconventional superconductors often have complex phase diagrams, with superconductivity emerging near other states of matter, such as antiferromagnetism or pseudogaps [17]. This points towards a deep connection between superconductivity and electron correlations, i.e., strong electron-electron interactions that significantly influence the electronic structure and transport properties.

Understanding superconductivity, particularly in unconventional systems, remains one of the most challenging and active areas of research in condensed matter physics. Beyond its fundamental importance, superconductivity holds vast technological promise in quantum computing (e.g., qubits based on Josephson junctions), magnetic resonance imaging (MRI), magnetic levitation, and lossless energy transmission.

3.2. Topological Materials

Topological materials possess electronic states protected by the topology of their energetic structure, and not only by symmetry [18]. For example, topological insulators (Figure 7) are bulk insulators but have conducting surface/edge states that remain stable and robust due to time-reversal symmetry. These surface states cannot be removed by small perturbations or defects, which makes them very stable [19]. This makes them highly suitable for fault-tolerant quantum computing, as topology-based quantum states can be inherently protected from external disturbances.

Additionally, topological superconductors as well as Weyl and Dirac semimetals are also a part of this class of quantum materials [20]. These systems exhibit gapless surface states or show unusual transport phenomena, such as the chiral anomaly, a quantum effect manifesting as an asymmetric particle flow under parallel electric and magnetic fields [21].

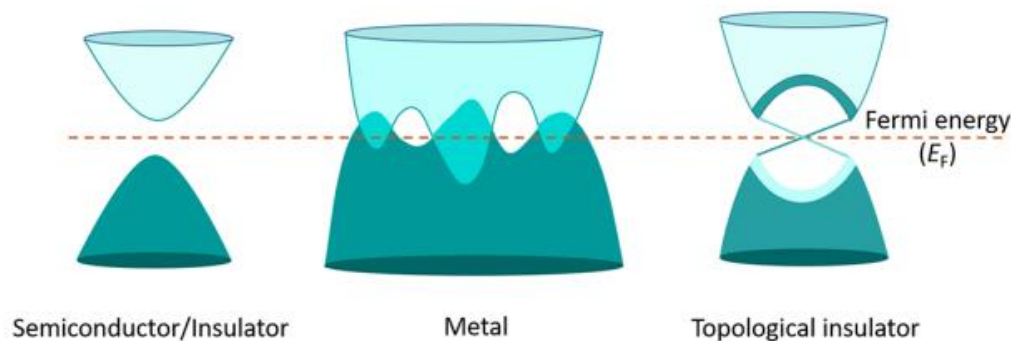


Figure 7. A schematic illustration of electronic band structures in various classes of solid-state materials. In semiconductors and insulators, the valence and conduction bands are separated by a finite energy band gap, which inhibits free charge carrier movement at low temperatures. In metals, the valence and conduction bands overlap, enabling high electrical conductivity. In topological insulators, band inversion leads to a band gap in the bulk electronic structure while simultaneously giving rise to conducting topological surface states characterized by linearly dispersing Dirac cone features [22].

Topological materials merge quantum mechanics, geometry, and mathematics within materials science, representing one of the most exciting frontiers in modern condensed-matter physics and chemistry.

3.3. Quantum Spin Systems

Quantum Spin Systems include a variety of materials and models in which magnetic properties are governed entirely by quantum-mechanical effects, and not by classical mechanisms such as ferromagnetism or antiferromagnetism. One of the most intriguing examples of these systems is the quantum spin liquid (QSL), a novel quantum phase of matter characterized by the absence of long-range magnetic order even at absolute zero [23].

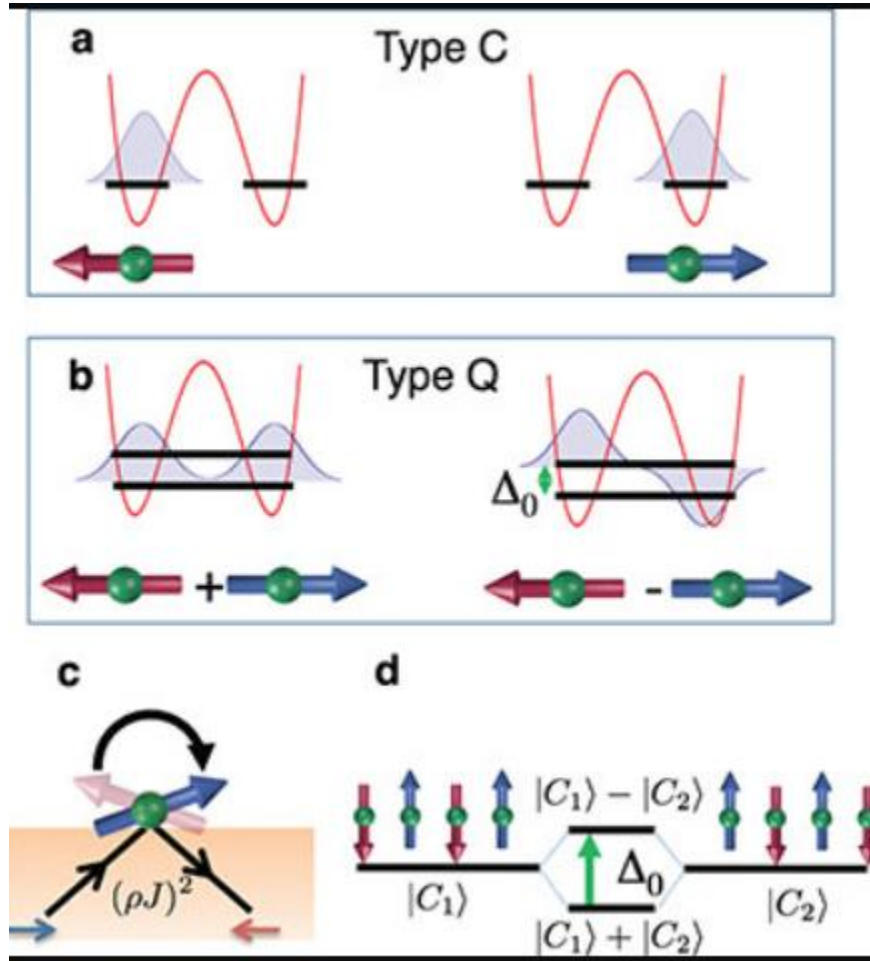


Figure 8. Two types of quantized spin systems: (a) Schematic of a type-C spin system with an easy axis and two degenerate ground states, each carrying a finite magnetic moment. (b) Type-Q spin system, where quantum spin tunneling (QST) leads to the formation of bonding and antibonding linear combinations of states with opposite magnetization, separated by the QST splitting. (c) Illustration of the Kondo exchange interaction between a single magnetic atom and conduction electrons, which becomes quenched as the product of the conduction electron density of states and the Kondo exchange increases. (d) Depiction of two classically degenerate Néel states for spin chains (denoted $\uparrow\downarrow\uparrow\downarrow$ and $\downarrow\uparrow\downarrow\uparrow$), along with the type-Q bonding and antibonding states and their associated QST splitting [24].

As opposed to classical magnets, in which electron spins align parallel (ferromagnetism) or antiparallel (antiferromagnetism), no static spin ordering is present in QSL due to strong quantum fluctuations that prevent it. Instead, the ground state is highly entangled: the magnetic moments remain dynamic and disordered and never “freeze” into a regular pattern [23] (Figure 8).

3.4. Strongly Correlated Electron Systems

Strongly correlated electron systems represent a class of materials in which electron-electron interactions are essential in determining their physical properties, which is why electrons cannot be treated as independent particles but rather as parts of an entangled system [25]. These materials exhibit complex and often counterintuitive behaviors, such as Mott insulation. Mott insulation occurs when a material expected to be a metal according to the band theory displays insulating behavior due to strong Coulomb repulsion [26]. Other examples include strange metals without well-defined quasiparticles, and heavy fermions with effective masses hundreds of times that of a free electron. A classic example is shown in Figure 9.

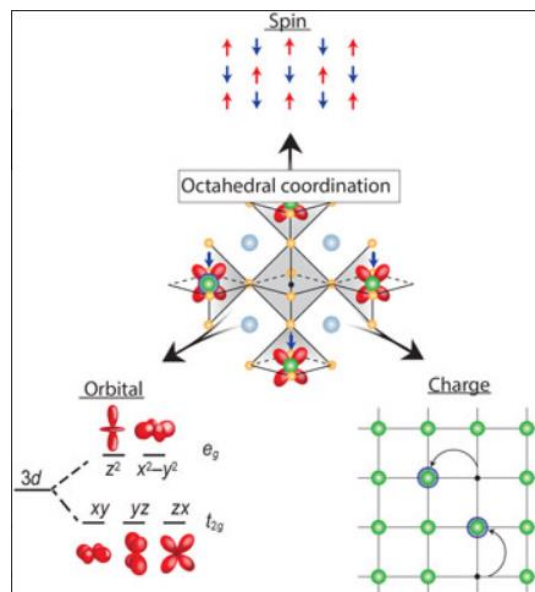


Figure 9. Octahedral coordination of vanadium ions, combined with strong electron correlation, couples spin, orbital, and charge degrees of freedom, giving rise to competing ground states and diverse electronic and optical properties [27].

Due to intense local interactions and quantum fluctuations, these systems frequently have complex phase diagrams featuring magnetic, superconducting, and nematic phases [17], as well as quantum critical points at zero temperature [28]. Typical examples include high-temperature superconductors (e.g., cuprates), nickelates [29], ruthenates [30], f-electron intermetallics (e.g., CeCoIn₅, URu₂Si₂) [30], and low-dimensional organometallic materials [31]. Theoretical understanding of these materials is based on models like the Hubbard [32] and Anderson [33] models as well as on contemporary methods such as dynamical mean-field theory (DMFT), which joins local quantum dynamics with the system's global properties [34].

3.5 Low-Dimensional and Nanostructured Quantum Systems

Quantum low-dimensional and nanostructured materials comprise unique physical systems in which particle motion is confined to one (1D), two (2D), or even zero (0D) dimensions [35]. This confinement leads to pronounced quantum effects that are absent in three-dimensional (3D) materials by amplifying quantum fluctuations and interactions, resulting in specific properties such as quantum localization, tunneling, exciton formation, and fractional excitations (Figure 10). Classic examples include graphene [36] and other 2D materials (e.g., MoS₂, h-BN) [37,38], 1D nanostructures like carbon nanotubes [39] and quantum wires, as well as zero-dimensional quantum dots, which act as “artificial atoms” with discrete energy levels [40]. Quantum interference [41], the Kondo effect [42], the quantum Hall effect [43], and the quantum spin Hall effect [44] emerge in such systems, making them adequate for fundamental quantum phenomena research as well as for usage in nanoelectronics, quantum dots for qubits, sensors, and optoelectronic devices [45,46]. The development of heterostructures with different 2D layers further enables engineering of quantum properties through interlayer coupling, twist-angle control (“twistronics”), and manipulation of charge, spin, and layer degrees of freedom [47].

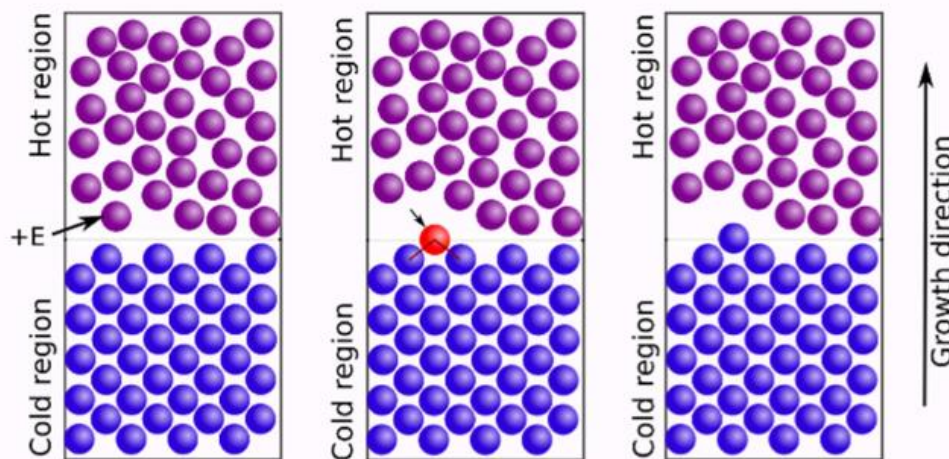


Figure 10. Schematic two-dimensional cross-section of a slab-like nanosystem with two distinct states, locally differentiated by temperature. An atom or molecule in the hotter region (shown in red) can acquire a quantum of thermal energy sufficient to cross the diffuse interface into a colder, more structurally ordered region. Upon entering the colder region, the particle dissipates this energy, for example, through bond formation – a quantum-mechanical process - thereby promoting the orderly growth of the colder grain [48].

4. Fundamental Quantum Phenomena in Materials

The extraordinary properties of quantum materials stem from the manifestation of core quantum-mechanical principles on macroscopic scales. These phenomena typically transpire from collective behavior of electrons, spins, or lattice vibrations and are responsible for the emergence of novel phases and functionalities. This section describes the key quantum effects that comprise the basis of quantum-material behavior.

4.1 Quantum Coherence and Entanglement

Quantum coherence refers to the preservation of phase relationships between quantum states, enabling the occurrence of phenomena such as superposition and interference [3]. In quantum materials, coherence is essential for effects like superconductivity, where Cooper pairs condense into a macroscopic coherent state. Quantum entanglement (Figure 11), the nonlocal correlation between particles, plays a central role in systems such as quantum spin liquids, topological phases, and proposed qubit systems for quantum computing [25]. Maintaining coherence and entanglement at the macroscopic scale is key to the establishment of robust quantum technologies and providing the basis for advances in quantum computing, communication, and sensing.

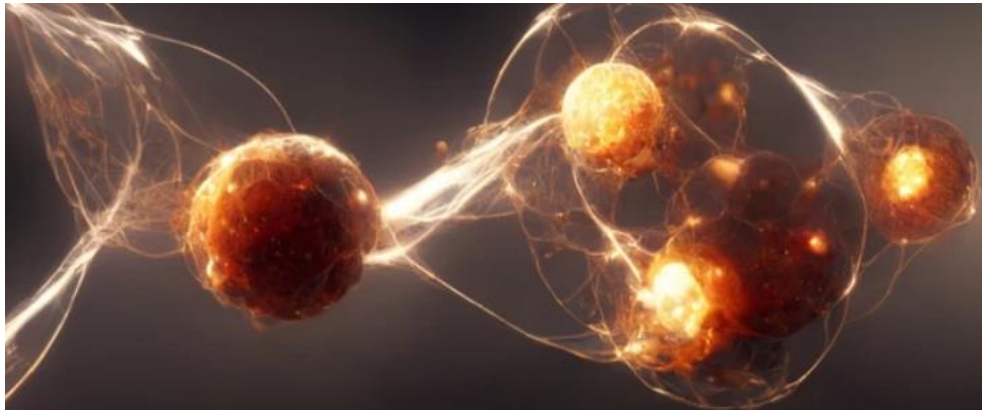


Figure 11. Quantum entanglement concept with particles and energy flow.

4.2 Topological Protection

Topological protection transpires when quantum states are stabilized by global features of the system's wavefunction rather than by local symmetries [5]. This concept is crucial to the robustness of edge states in topological insulators and superconductors, where electron backscattering by nonmagnetic impurities is forbidden.

Topological insulators are materials that behave as conventional insulators in the bulk, but their surfaces/edges behave as special quantum electrical conductors [5,19]. Such states are resistant to deformations or impurities, as they are stabilized by global properties of the wavefunction, such as topological quantum number (e.g., a winding number) [6]. Electrons can therefore propagate without energy loss from impurity scattering, making topological insulators exceptionally stable and precise in usage for quantum technologies.

Topological superconductors are similar to topological insulators but have more complex properties, since superconductivity can occur at their edges/surfaces [49]. These materials are essential for the development of quantum computing [50], as their edges enable the manipulation of qubits with a high degree of stability and precision.

Topological protection ensures that quantum states remain intact even in the presence of defects, irregularities, or impurities within the material [51]. This is particularly important because, in conventional conductors, such imperfections scatter electrons, leading to energy loss and degraded device performance (fig. 9).

By contrast, topological materials are inherently immune to these perturbations [51], making them indispensable for the development of ultra-precise devices like topological quantum computers. In such systems, qubits are used for quantum operations that are exceptionally resistant to external disturbances, hence providing the stability required for complex quantum computations.

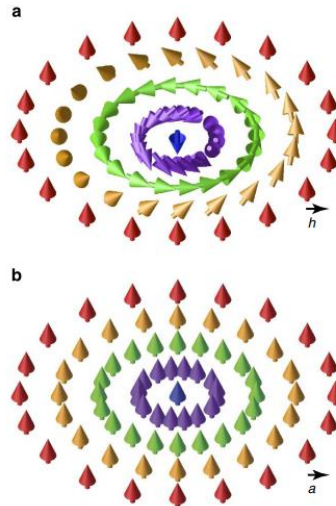


Figure 12. Topological protection of bound states against the hybridization. Topological origin of bulk localization. Schematic figures showing the topological structure of the unit vectors \vec{h} and \vec{a} in a 2D space. (a) \vec{h} forms a skyrmion configuration with the unit Pontryagin number, while (b) \vec{a} makes a topologically trivial structure. \vec{h} and \vec{a} are parallel (antiparallel) at the boundary (at the centre) [52].

4.3 Quantum Fluctuations and Zero-Point Motion

Quantum fluctuations are an inevitable, fundamental aspect of all quantum systems, persisting even at absolute zero. These fluctuations stem from the Heisenberg uncertainty principle, which limits the precision with which one can measure parameters such as position and momentum [53]. Hence, even in systems cooled to the lowest temperatures attainable, where classical physics would predict a complete lack of particle movement, they still undergo quantum fluctuations related to their wavefunctions.

Quantum fluctuations can be essential for the behavior of quantum materials, especially in systems where tendencies towards ordered structures are too weak to prevail. In such cases, fluctuations may dominate, giving rise to exotic phases that are absent in classical materials. For example, quantum spin liquids represent special quantum states in which microscopic spins never settle into conventional magnetic order but remain “liquid-like” down to the lowest temperatures, which is a direct result of strong quantum fluctuations preventing spin alignment [23].

Moreover, quantum fluctuations (Figure 13) underlie quantum critical points, which are transition points in a phase diagram where a material is in the state right in between two distinct phases and exhibits highly unusual, unpredictable behavior [54]. These critical points are essential for understanding quantum phase transitions, as fluctuations at phase boundaries can significantly alter the physical properties of a material.

Zero-point motion is another aspect of quantum systems present even at absolute zero [55]. Even when classical thermodynamics would predict the absence of particle motion, atoms or spins retain their

dynamics and are in constant movement due to their wave-like nature. This effect is especially pronounced in materials containing light elements (e.g., hydrogen) [55] or in systems with strongly anharmonic potentials, where atoms deviate from ideal harmonic behavior [56]. In such systems, zero-point motion can significantly affect structural stability, lattice dynamics, and phase transitions.

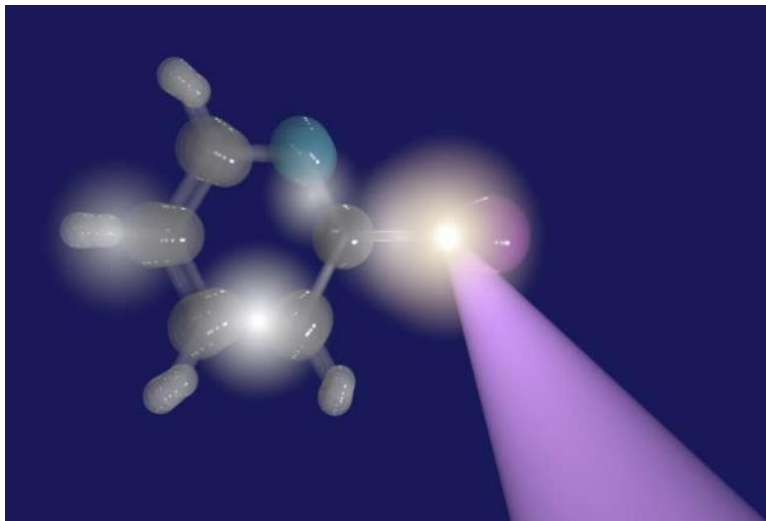


Figure 13. Imaging collective quantum fluctuations of the structure of a complex molecule. High-intensity X-ray laser pulses trigger controlled explosions of molecules, making it possible to capture high-resolution images of molecular structures [57].

For instance, in crystals with light constituents, zero-point motion can shift energy equilibria, triggering unexpected phase changes or instabilities under certain conditions. In low-energy topological materials, these fluctuations may help preserve or change topological properties by enabling transitions between different phases or by stabilizing quantum states [58].

Quantum fluctuations and zero-point motion are thus pivotal to understanding quantum materials, especially in the context of emerging technologies that utilize quantum effects, such as quantum computing and high-precision quantum sensing, where stability and precision at the smallest scales are of paramount importance.

4.4 Strong Electron Correlations

In many quantum materials, the Coulomb interaction between electrons is comparable to and sometimes even exceeds their kinetic energy, leading to strong electron-electron correlations [59]. These correlations represent a key feature of many quantum systems, separating them from traditional metals described by Fermi liquid theory, where electrons behave as relatively independent parts of the system. In systems with strong correlations, however, interactions become strong enough that they significantly affect the system's behavior, making it more complex and harder to predict when compared to classical models [60] (Figure 14)

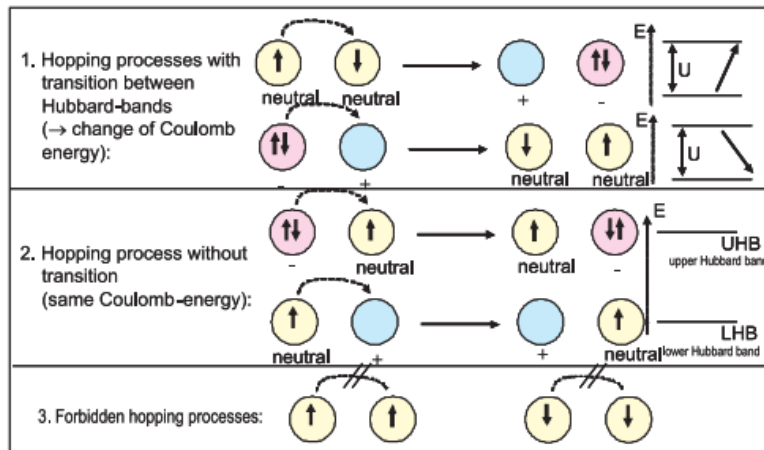


Figure 14. Illustration of hopping processes between neighboring atoms together with their corresponding energy scales [61].

One of the most significant features of strongly correlated systems is their ability to give rise to novel, non-traditional phenomena that are absent in metals. These include Mott insulating behavior, the emergence of heavy-fermion systems, charge-ordering transitions, and non-Fermi-liquid behavior.

a) Mott Insulating Behavior

A Mott transition is a quantum phase transition in which a material that band theory predicts to be metallic (which is often the case with high electron density materials) becomes an insulator instead [62]. This effect occurs when strong Coulomb interactions prevent electrons from moving freely through the material, leading to insulating behavior.

b) Heavy-Fermion Systems

In these systems with strong correlations, electrons can form so called heavy fermions that behave like particles with effective masses hundreds of times larger than expected, leading to unusual thermal and electric properties at low temperatures [63].

c) Charge Ordering

In systems where interactions between electrons are pronounced, they may spontaneously organize into spatially ordered patterns, i.e., charge-ordered phases. Rather than behaving as independent particles, they become localized and grouped, leading to periodic charge density changes that can significantly influence electrical and magnetic properties and result in insulating behavior, unconventional phase transitions, or complex magnetic structures that cannot be explained by free-electron models [64].

d) Non-Fermi-Liquid Behavior

In strongly correlated systems, phenomena that are difficult to explain using the traditional theory of Fermi liquids can emerge. In these materials, electrons behave in ways that significantly differ from the classical free fermion model. These systems exhibit non-traditional thermal and electrical properties such as unusual variations in electrical resistivity at different temperatures [65].

Due to strong correlations among electrons, these properties can lead to the development of novel and unconventional quantum phenomena, such as non-traditional superconductivity and magnetism [16]. For example, the superconductivity observed in cuprates (such as YBCO or BSCCO), where electrons form

Cooper pairs, can only be understood by taking these interactions into account [17]. This is reminiscent of f-electron compounds (such as those involving actinides and lanthanides), which give rise to antiferromagnetism and other complex quantum states [65].

Strong correlations also drive the formation of complex phase diagrams that may include various phases such as superconductivity, magnetism, and metal-insulator transitions [66]. These phases often emerge under specific conditions, when interactions become sufficiently strong to enable the appearance of new quantum phases that are absent in conventional materials.

Ultimately, these strong correlations offer a remarkable opportunity for the development of next-generation technologies based on quantum materials, including quantum computing, quantum sensors, and other applications that utilize emerging quantum effects.

4.5 Quantum Phase Transitions and Criticality

Quantum phase transitions refer to changes in the state of a material that occur at absolute zero (0 K) that are not driven by thermal fluctuations, but by non-thermal parameters such as pressure, magnetic field, chemical doping, or mechanical strain [53]. Unlike classical phase transitions (such as ice melting), quantum phase transitions are led by quantum fluctuations, which are dominant in this regime.

Near the so-called quantum critical point (QCP) (Figure 15), quantum fluctuations become scale-invariant, meaning they do not depend on temporal or spatiotemporal scales, and can significantly modify the material's physical properties [67]. Quantum criticality is believed to be a key mechanism underlying the emergence of many exotic phases of matter, including high-temperature superconductivity, nonmagnetic metallic phases with strong fluctuations, and unstable quantum states found in heavy-fermion systems and spin liquids [68].

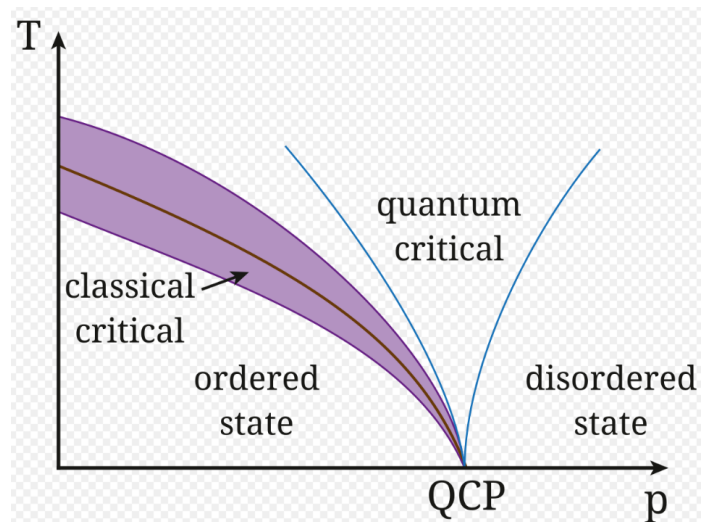


Figure 15. Diagram of temperature (T) and pressure (p) showing the quantum critical point (QCP) and quantum phase transitions [69].

5. Experimental Techniques for Quantum Materials Characterization

The study of quantum materials requires advanced experimental techniques capable of probing quantum effects at atomic, electronic, and mesoscopic scales. These methods provide insight into the structural, electronic, magnetic, and dynamic properties of materials, and are essential for understanding the nature of fundamental quantum phenomena. This section highlights key experimental approaches that are widely used in the characterization of quantum materials.

5.1 X-ray and Neutron Scattering

X-ray diffraction (XRD) remains a fundamental technique for determining crystal structures, identifying phase composition, and detecting subtle lattice distortions associated with quantum phase transitions. Beyond conventional XRD, synchrotron radiation enables high-resolution investigations of lattice strain, orbital ordering, and charge density waves [70].

Neutron scattering is an especially powerful technique for testing magnetic structures and excitations due to neutrons' intrinsic magnetic moment [71]. Techniques such as elastic neutron scattering reveal static spin arrangements, while inelastic neutron scattering can capture spin dynamics, lattice vibrations (phonons), and even the emergence of quasiparticles such as magnons and rotons. Neutron scattering is particularly valuable for studying zero-point fluctuations and the behavior of quantum spin liquids [72].

5.2 Scanning Probe Microscopy (SPM)

Scanning probe microscopy encompasses techniques such as scanning tunneling microscopy (STM) and atomic force microscopy (AFM), which enable real-space imaging of surfaces with atomic-scale resolution. STM is particularly important for mapping the local electronic density, revealing traces of superconducting gaps, topological edge modes, and other quantum phenomena. The spin-polarized variant of the technique allows the examination of magnetic properties at the atomic level, paving the way for the study of spin textures and quantum magnetic states at the nanoscale [73]. These methods are essential for understanding local quantum effects such as quasidegenerate electronic states, Majorana quasiparticles, or defect localized modes, that cannot be detected through bulk measurements [74].

AFM, in contrast, utilizes the mechanical interaction between the probe and the sample surface in order to map both topography and local forces (e.g., van der Waals, electrostatic, magnetic). Special AFM modalities, including Kelvin probe force microscopy (KPFM) and magnetic force microscopy (MFM), enable additional functional characterizations of electrical and magnetic properties of quantum materials [75].

Thanks to their spatial resolution and sensitivity, SPM techniques have become indispensable tools for studying quantum phenomena such as quantum interference, local symmetry breaking, and electronic nematicity in a wide range of advanced materials.

5.3 Spectroscopic Techniques

Angle-resolved photoemission spectroscopy (ARPES) is a key tool for mapping the electronic band structure of materials while preserving information about the electron's momentum. ARPES has played an essential role in identifying topological surface states, Dirac cones, and Fermi-surface

instabilities in quantum materials. This technique enables the direct observation of the quantum-mechanical properties of electronic states and provides invaluable insight into the complex electronic behavior of high-temperature superconductors and topological insulators [76].

Raman spectroscopy and infrared (IR) spectroscopy examine vibrational modes and electronic excitations, delivering information on electron-phonon coupling, structural phase transitions, and collective excitations associated with quantum criticality [77]. Raman spectroscopy, in particular, is particularly useful for detecting symmetry changes and local ordering that accompany quantum phase transitions.

Electron spin resonance (ESR) and nuclear magnetic resonance (NMR) are also widely used to investigate spin dynamics, local magnetic fields, and low-energy excitations, especially in strongly correlated electron systems [78]. These methods enable detailed characterization of quantum states, such as spin liquids and nematic order, through precise measurements of relaxation times and local interactions.

5.4 Quantum Transport Measurements

Measurements of electrical conductivity, the Hall effect, and magnetoresistance as functions of temperature, magnetic field, and pressure offer fundamental insights into the quantum behavior of charge carriers. These techniques elucidate basic transport processes, electron localization, and the transitions between metallic and insulating states.

Quantum oscillations, such as the Shubnikov-de Haas and de Haas-van Alphen effects, reveal the geometry of the Fermi surface and the renormalization of electron effective mass, indicating the presence of strong particle correlations and topological characteristics of the system [79]. Accurate analyses of these oscillations can identify discrete Landau levels and quantum coherence in complex materials [80].

In topological materials, quantized conductance and the anomalous Hall effect serve as direct evidence of nontrivial topological order, which is often protected by symmetry and robust against defects [81]. These phenomena are of particular importance for the development of quantum electronics and spintronics, where quantum properties are harnessed for information transfer and processing [82].

In superconductors, transport measurements determine critical fields, critical currents, and the nature of the pairing mechanism (singlet vs. triplet, conventional vs. unconventional). They can also reveal quantum vortex states and coherence limits, which are crucial for understanding quantum phase transitions and designing new materials for quantum computing applications.

5.5 Time-Resolved and Ultrafast Techniques

Recent advances in pump-probe spectroscopy and ultrafast electron diffraction have enabled the study of quantum materials on femtosecond (10^{-15} s) timescales, opening a new dimension in our understanding of the ultrafast processes underlying quantum phenomena [83]. These techniques rely on initiating a response in the material using an ultrashort “pump” pulse, followed by a “probe” pulse that measures the system’s response, thus providing time-dependent insights into quantum transitions [84].

By employing these techniques, it is possible to directly observe nonequilibrium processes such as photoinduced phase transitions, transient quantum states, and collective excitations that cannot be detected in stationary conditions [85]. The ability to identify and track transient material states with unique electronic, structural, or magnetic properties, some of which may be stabilized in quantum regimes through careful tuning of experimental parameters, is of particular importance.

Time-resolved measurements are of great importance for investigating the dynamics of quantum coherence, the onset and decay of superconductivity under non-equilibrium conditions, and the evolution of topological states in real time. They also enable insight into femtosecond spin dynamics, charge redistribution, and phonon-electron interactions that are key to understanding and controlling the functional properties of quantum materials [86].

The development of these techniques represents a crucial step towards the discovery and manipulation of quantum phenomena that can have fundamental importance for quantum technologies, including ultrafast memory devices, quantum switches, and photoinduced quantum phases [87].

6. Quantum Materials in Contemporary Technologies

Quantum materials are not only a subject of fundamental scientific interest but are also at the heart of revolutionary technological innovations. Their unique properties, which stem from quantum coherence, topological protection, and strong correlations, are increasingly exploited for next-generation technologies in information processing, sensing, and energy applications. The following section examines some of the most promising technological directions enabled by quantum materials.

6.1 Quantum Computing

Quantum computing utilizes the principles of superposition and entanglement to perform calculations that are unachievable for classical computers. Certain quantum materials provide the physical platforms necessary for building qubits. For example:

- **Topological superconductors** are proposed hosts for Majorana zero modes [74], quasiparticles that are intrinsically protected against local perturbations and offer a pathway to error-resilient quantum computing. Non-Abelian statistics make them optimal for so-called topological qubits.
- **Spin qubits** can be realized in quantum dots and defect centers (e.g., nitrogen-vacancy (NV) centers in diamonds), where quantum coherence is maintained in solid state and at relatively high temperatures compared to other systems [88].
- **Superconducting circuits** made from low-loss materials such as aluminum and niobium are at the base of many state-of-the-art quantum processors, including those being developed by leading companies like Google, IBM, and Rigetti.

The development of materials with longer coherence times, higher operating temperatures, and scalable fabrication techniques remains one of the major challenges in advancing quantum computing [89]. In this context, new classes of quantum materials, such as quantum spin liquids, topological insulators, and high-entropy solid solutions, are being actively investigated [90].

Furthermore, the merging of quantum materials and conventional semiconductor technologies presents both a challenge and an opportunity for hybrid devices that could represent a transition between classical and quantum computing systems [91].

6.2 Quantum Sensing and Metrology

Quantum materials enable the development of sensors with unprecedented sensitivity and precision, opening new possibilities in both scientific and technological applications. Some of the most prominent examples include:

- Superconducting quantum interference devices (SQUIDs) can detect extremely weak magnetic fields in the femtotesla range with high accuracy [92]. Such devices are indispensable in neurobiology (e.g., brainwave measurement), geophysics, and fundamental research.
- Topological insulators and Dirac/Weyl semimetals, where surface or bulk electronic configurations are extremely sensitive and responsive to external perturbations (such as magnetic or electric fields) [93]. These properties make them strong candidates for high-resolution sensors capable of detecting weak electromagnetic signals or even subtle quantum-gravitational effects.
- Quantum defects in materials like diamond (e.g., nitrogen-vacancy (NV) centers) can be employed for nanoscale magnetometry, thermometry, and even visualization of single molecules [94]. Their ability to preserve quantum coherence at room temperature makes them particularly useful for portable and biocompatible devices.

Quantum sensors based on these materials promise a revolution across numerous fields, from medical diagnostics (e.g., precise measurement of electrical signals in cells) and materials research to the detection of dark matter, gravitational waves, and other aspects of fundamental physics [95]. A particularly active area of research involves the integration of quantum sensors with micro/nanoelectronic platforms in the development of compact quantum devices. Such integration would enable widespread real-world applications ranging from precision navigation without GPS to next-generation medical equipment and quantum communication networks [96].

6.3 Spintronics and Quantum Information Storage

Spintronics (spin-electronics) exploits the electron's spin, in addition to its charge, to store and manipulate information, paving the way for a new generation of energy-efficient, faster computing devices [97]. Quantum materials offer a rich spectrum of opportunities for this technology due to their unique spin architectures and quantum effects. Some of the key classes of materials include:

- Magnetic topological insulators, which combine spin-orbit coupling with magnetic order, enable dissipationless spin transport along surfaces.
- Two-dimensional magnetic materials (e.g., CrI_3 , Fe_3GeTe_2) allow control of magnetism at the atomic level, which is crucial for ultra-compact memory units and quantum logic circuits [98].
- Antiferromagnetic spintronic systems, which offer advantages such as high-frequency dynamics, robustness against external magnetic fields, and ultrafast spin dynamics, enable stable and fast manipulation of spin states.

For the development of functional spintronic and quantum-information devices, materials with long spin-coherence times and efficient spin-to-charge (and charge-to-spin) conversion are critical. A major challenge, as well as an opportunity, lies in the integration of these materials onto CMOS-compatible platforms and maintenance of their stability at room temperature. Using quantum materials in spintronics paves the way for the development of quantum memories that could replace conventional DRAM and

flash storage, as well as spin-based neural networks that mimic the human brain's functionality in hardware form [99].

6.4 Energy Applications

Quantum materials also hold enormous potential in the field of energy technology, offering solutions that can significantly improve the efficiency, reliability, and sustainability of energy systems. Their unique quantum properties enable functionalities that surpass the limits of conventional materials. Some of the most important research directions include:

- High-temperature superconductors, which allow lossless electrical power transmission and the development of ultra-efficient electromagnets for use in power grids, medical imaging (e.g., MRI), and energy storage systems (such as flywheel storage) [100].
- Strongly correlated oxides with tunable metal-insulator transitions [101], which are being explored for neuromorphic computing and adaptive energy devices that can autonomously change their functionality in response to external conditions (e.g., temperature, voltage, illumination).
- Photocatalytic quantum materials (e.g., doped CeO₂ (ceria) and layered oxides), which are promising candidates for solar-to-chemical energy conversion (e.g., hydrogen production from water) due to enhanced electron-hole separation and quantum-controlled reaction dynamics [102].

Additionally, quantum materials are being increasingly investigated for thermoelectric applications, where quantum confinement and phonon scattering can boost the efficiency of converting heat into electricity [103]. Exploiting the quantum properties of materials for energy efficiency and sustainability is a groundbreaking field at the interface of fundamental science and technological solutions to global challenges such as decarbonization, renewable energy, and smart energy grids. In this context, synthesis, characterization, and engineering of quantum materials with precisely controlled properties is becoming essential for a future in energy based on sustainable resources.

7. Current Challenges and Future Perspectives in Quantum Materials Research

Despite significant progress, the field of quantum materials research faces numerous challenges that must be overcome to fully use their potential. Understanding the complex interplay of quantum effects, developing scalable synthesis methods, and achieving reliable technological implementations remain highly demanding tasks. This section examines the key obstacles and outlines directions for future investigation.

7.1 Materials Synthesis and Control

Producing quantum materials of required purity, stoichiometry, and structural precision remains one of the greatest challenges in this field. Even minimal deviations in composition or crystal structure can significantly alter a material's quantum properties, including superconductivity, topological order, and spin-liquid behavior [104]. Thus, achieving reproducible and optimized synthesis is a prerequisite for advancing quantum technologies.

Advances in thin-film growth techniques, such as molecular beam epitaxy (MBE) [105], pulsed laser deposition (PLD) [106], and chemical vapor deposition (CVD) [107], permit atomic-scale control over material layers, which is crucial for stabilizing desired quantum phases. Meanwhile, self-assembly methods [108] and sol-gel synthesis [109] provide cost-effective routes for producing quantum materials on larger scales.

A particular challenge lies in designing heterostructures and artificially engineered composites where multiple quantum phenomena can coexist or compete - for example, the coexistence of superconductivity and magnetism [110], or the interplay between spin-orbit coupling and topological states [111]. In such systems, precise control of interfaces between layers becomes critical, since an interface may either give rise to new quantum behavior or act as a site of functional degradation.

Beyond experimental hurdles, combining theoretical modeling with AI-driven materials design is increasingly used to predict stable phases and guide the synthesis of compositions with targeted quantum effects [112]. However, the successful realization of these data-driven predictions still depends on advanced experimental control.

7.2 Theoretical Modeling and Simulation

Modeling quantum materials accurately is an extraordinarily complex task due to strong electron-electron correlations, topological characteristics, and quantum fluctuations - features that often exceed the capabilities of standard numerical methods. Classical approximations, such as density functional theory (DFT), frequently fail to capture collective quantum states, pointing towards a need for more computationally intensive, advanced approaches.

In this context, several advanced theoretical methods are being developed and applied:

- Dynamical Mean-Field Theory (DMFT): Captures local correlations in strongly interacting systems, such as Mott insulators and complex oxides [34]
- Density Matrix Renormalization Group (DMRG) [113]: Especially well-suited for one-dimensional systems and low-entropy systems, as it can highly accurately track quantum-entanglement structures
- Quantum Monte Carlo (QMC) Simulations: Offer statistically exact results for thermodynamic properties, but often suffer from the “sign problem” in fermionic systems [114]
- Machine Learning (ML) Methods: Increasingly used to predict phase diagrams, generate efficient Hamiltonians, and classify quantum states from experimental data [115]

Aside from developing new algorithms, connecting microscopic theoretical models with macroscopic experiments, such as transport measurements, spectroscopic signals, and quantum criticality, remains a major challenge. For example, understanding how collective excitons, spinons, or quasiparticles emerge from the underlying lattice and interact requires multiscale modeling and a deep synergy between theory and experiments. Moreover, simulating quantum systems with multiple degrees of freedom (spin, charge, orbital degeneracy) under external parameters (e.g., pressure, temperature, magnetic field) demands enormous computational resources. In this context, quantum-computer-based simulation of quantum materials becomes one of the most exciting frontiers of the future and leads to the point at which quantum materials themselves are used to study other quantum materials.

7.3 Characterization in Extreme Conditions

Many quantum phenomena manifest only under extreme conditions such as ultralow temperatures (millikelvin range), ultrahigh magnetic fields (exceeding 30-40 T), and high pressures (multiple GPa range) [116]. Such regimes present big experimental challenges that require sophisticated and precise equipment (e.g., dilution refrigerators, superconducting magnets, and diamond-anvil cells).

Developing in situ and operando characterization techniques that enable real-time measurements under variable conditions is crucial for studying quantum phase transitions, metastable equilibrium states, and quantum-coherence dynamics [117]. Such measurements are essential for understanding quantum criticality, spin-liquid states, and topological transitions, as well as for discovering new forms of matter. Achieving these goals requires close collaboration between condensed-matter physicists, engineers, and experimental scientists in order to expand the boundaries of testing conditions.

7.4 Integration into Devices

The transition from fundamental discoveries to functional quantum devices is a particularly challenging step. Quantum coherence, a key property for quantum technologies, can be easily disrupted by environmental influences, including thermal fluctuations, material defects, mechanical strain, and electronic noise [118]. Consequently, engineering of robust, scalable, and reproducible components based on quantum materials is still at an early stage of development.

Key requirements for successful integration include:

- Protecting quantum states through topological mechanisms [119]: For example, isolating Majorana quasiparticles that are inherently immune to local perturbations
- Implementing quantum error correction in logical circuits [120]
- Integrating quantum materials with classical technologies, including CMOS compatibility, to facilitate hybrid devices and easier adoption within existing industrial infrastructure [121]

Designing interfaces between different quantum phases within a single device (e.g., coupling a superconductor to spintronic layers) also opens up possibilities for multifunctional quantum components, but it demands atomically precise control during manufacturing.

Progress in this field necessitates an interdisciplinary approach combining theoretical physics, materials science, nanofabrication techniques, and quantum engineering. Stable quantum platforms that operate reliably under realistic conditions and move towards commercial viability can only be developed through such synergy.

7.5 Future Perspectives

Looking ahead, numerous exciting research directions in quantum materials are coming to the forefront. These avenues not only deepen our understanding of quantum phenomena but also open pathways to innovations with far-reaching technological impact. Some key future directions include:

- Symmetry- and topology-driven materials design: Utilizing group-theoretical tools and topological quantum chemistry to systematically identify materials with desired quantum properties such as topological insulators, quantum spin liquids, or multi-component superconductors

- Discovering new quantum phases at interfaces and in “twisted” layered structures: For example, moiré superlattices [122] in graphene and related materials can host fractional quasiparticles, unconventional excitations, and collective effects absent from conventional phases
- Exploring quantum entanglement as a fundamental material property: This could lead to a new classification of quantum matter based on entanglement patterns rather than classical symmetry considerations, potentially enabling novel functionalities in quantum technology.
- Quantum materials for sustainable technologies, including quantum-enhanced energy harvesting, high-efficiency catalysis, and low-power information processing. These applications have the potential to address global challenges such as energy efficiency, decarbonization, and resource conservation.

The inherently interdisciplinary nature of quantum materials research, spanning condensed-matter physics, materials chemistry, computational science, and quantum information theory, ensures that this field will remain dynamic, challenging, and transformative for decades to come. With ever-improving experimental and theoretical tools, and as quantum computers are increasingly used to simulate complex quantum systems, quantum materials are bound to be the foundation of future technologies.

8. Conclusion

Quantum materials represent one of the most exciting and promising frontiers in modern condensed-matter physics and materials science. In these systems, quantum-mechanical principles such as coherence, entanglement, topological protection, and strong electron correlations manifest themselves on macroscopic scales, giving rise to extraordinary phenomena that defy the laws of classical physics. Examples include superconductivity, topological phases, quantum spin liquids, and unconventional electronic behavior, all of which hold the potential for revolutionary technological applications.

Historically, the development of quantum materials has been tightly connected with theoretical breakthroughs such as Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity and the band topology framework, as well as with experimental advances that have allowed direct observation and control of quantum states in materials. Today, quantum properties of these systems are already the basis of the development of quantum computers, ultra-sensitive sensors, spintronic devices, and novel energy solutions.

Despite this remarkable progress, many challenges remain. Researchers must achieve exceptionally precise control over material composition and structure, develop predictive theoretical models that account for strong correlations and quantum fluctuations, perform experiments under extreme conditions (e.g., millikelvin temperatures or gigapascal pressures), and successfully integrate quantum materials into scalable devices. Meeting these goals calls for coordinated, interdisciplinary efforts that bring together physics, chemistry, computational science, and engineering.

New paradigms, such as designed quantum materials, machine-learning–guided discoveries, and real-time tracking of quantum dynamics, promise to accelerate the pace of novel advancements. In the years ahead, quantum materials will unquestionably play a central role in the development of advanced technologies, not only by deepening our fundamental understanding but also by delivering concrete solutions to global challenges in computing, communication, energy, and environmental protection.

Continued exploration of these materials will enable the discovery of new quantum states, unexpected functionalities, and previously unseen physical principles, further solidifying their importance in the future of science and technology.

References:

- [1] H.K. Onnes, Further experiments with liquid helium. C. On the change of electric resistance of pure metals at very low temperatures, etc. IV. The resistance of pure mercury at helium temperatures, in: *sn*, 1911: pp. 1910–1911.
- [2] J. Bardeen, L.N. Cooper, J.R. Schrieffer, Microscopic theory of superconductivity, *Physical Review* 106 (1957) 162.
- [3] J. Bardeen, L.N. Cooper, J.R. Schrieffer, Theory of Superconductivity, *Phys. Rev.* 108 (1957) 1175–1204. <https://doi.org/10.1103/PhysRev.108.1175>.
- [4] E. Mendez, L. Esaki, L. Chang, Quantum Hall effect in a two-dimensional electron-hole gas, *Physical Review Letters* 55 (1985) 2216.
- [5] M.Z. Hasan, C.L. Kane, Colloquium: topological insulators, *Reviews of Modern Physics* 82 (2010) 3045–3067.
- [6] X.-G. Wen, Colloquium: Zoo of quantum-topological phases of matter, *Reviews of Modern Physics* 89 (2017) 041004.
- [7] M.A. Hidalgo, Quantum hall effects in two-dimensional electron systems: a global approach, *Eur. Phys. J. Plus* 137 (2022) 58. <https://doi.org/10.1140/epjp/s13360-021-02173-6>.
- [8] A.K. Geim, K.S. Novoselov, The rise of graphene, *Nature Materials* 6 (2007) 183–191.
- [9] K.S. Novoselov, A.K. Geim, S.V. Morozov, D. Jiang, Y. Zhang, S.V. Dubonos, I.V. Grigorieva, A.A. Firsov, Electric field effect in atomically thin carbon films, *Science* 306 (2004) 666–669.
- [10] K.V. Klitzing, G. Dorda, M. Pepper, New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance, *Phys. Rev. Lett.* 45 (1980) 494–497. <https://doi.org/10.1103/PhysRevLett.45.494>.
- [11] A. Bansil, H. Lin, T. Das, *Colloquium* : Topological band theory, *Rev. Mod. Phys.* 88 (2016) 021004. <https://doi.org/10.1103/RevModPhys.88.021004>.
- [12] C. Pfleiderer, Superconducting phases of f -electron compounds, *Rev. Mod. Phys.* 81 (2009) 1551–1624. <https://doi.org/10.1103/RevModPhys.81.1551>.
- [13] G. Stewart, Unconventional superconductivity, *Advances in Physics* 66 (2017) 75–196.
- [14] A. Gurevich, Challenges and opportunities for applications of unconventional superconductors, *Annu. Rev. Condens. Matter Phys.* 5 (2014) 35–56.
- [15] D.N. Basov, T. Timusk, Electrodynamics of high- T_c superconductors, *Rev. Mod. Phys.* 77 (2005) 721–779. <https://doi.org/10.1103/RevModPhys.77.721>.
- [16] D.J. Scalapino, A common thread: The pairing interaction for unconventional superconductors, *Rev. Mod. Phys.* 84 (2012) 1383–1417. <https://doi.org/10.1103/RevModPhys.84.1383>.
- [17] B. Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, J. Zaanen, From quantum matter to high-temperature superconductivity in copper oxides, *Nature* 518 (2015) 179–186. <https://doi.org/10.1038/nature14165>.
- [18] X.-G. Wen, Topological Order: From Long-Range Entangled Quantum Matter to a Unified Origin of Light and Electrons, *ISRN Condensed Matter Physics 2013* (2013) 1–20. <https://doi.org/10.1155/2013/198710>.
- [19] L. Fu, C.L. Kane, Topological insulators with inversion symmetry, *Phys. Rev. B* 76 (2007) 045302. <https://doi.org/10.1103/PhysRevB.76.045302>.
- [20] N.P. Armitage, E.J. Mele, A. Vishwanath, Weyl and Dirac semimetals in three-dimensional solids, *Rev. Mod. Phys.* 90 (2018) 015001. <https://doi.org/10.1103/RevModPhys.90.015001>.
- [21] D.T. Son, B.Z. Spivak, Chiral anomaly and classical negative magnetoresistance of Weyl metals, *Phys. Rev. B* 88 (2013) 104412. <https://doi.org/10.1103/PhysRevB.88.104412>.
- [22] N. Kumar, S.N. Guin, K. Manna, C. Shekhar, C. Felser, Topological Quantum Materials from the Viewpoint of Chemistry, *Chem. Rev.* 121 (2021) 2780–2815. <https://doi.org/10.1021/acs.chemrev.0c00732>.

- [23] L. Savary, L. Balents, Quantum spin liquids: a review, *Rep. Prog. Phys.* 80 (2017) 016502. <https://doi.org/10.1088/0034-4885/80/1/016502>.
- [24] F. Delgado, S. Loth, M. Zielinski, J. Fernández-Rossier, The emergence of classical behaviour in magnetic adatoms, *EPL* 109 (2015) 57001. <https://doi.org/10.1209/0295-5075/109/57001>.
- [25] L. Amico, R. Fazio, A. Osterloh, V. Vedral, Entanglement in many-body systems, *Rev. Mod. Phys.* 80 (2008) 517–576. <https://doi.org/10.1103/RevModPhys.80.517>.
- [26] S. Sachdev, Understanding correlated electron systems by a classification of Mott insulators, *Annals of Physics* 303 (2003) 226–246. [https://doi.org/10.1016/S0003-4916\(02\)00024-6](https://doi.org/10.1016/S0003-4916(02)00024-6).
- [27] M. Brahlek, L. Zhang, J. Lapano, H.-T. Zhang, R. Engel-Herbert, N. Shukla, S. Datta, H. Paik, D.G. Schlom, Opportunities in vanadium-based strongly correlated electron systems, *MRS Communications* 7 (2017) 27–52. <https://doi.org/10.1557/mrc.2017.2>.
- [28] H.V. Löhneysen, A. Rosch, M. Vojta, P. Wölfle, Fermi-liquid instabilities at magnetic quantum phase transitions, *Rev. Mod. Phys.* 79 (2007) 1015–1075. <https://doi.org/10.1103/RevModPhys.79.1015>.
- [29] D. Li, K. Lee, B.Y. Wang, M. Osada, S. Crossley, H.R. Lee, Y. Cui, Y. Hikita, H.Y. Hwang, Superconductivity in an infinite-layer nickelate, *Nature* 572 (2019) 624–627. <https://doi.org/10.1038/s41586-019-1496-5>.
- [30] A.P. Mackenzie, Y. Maeno, The superconductivity of Sr₂RuO₄ and the physics of spin-triplet pairing, *Rev. Mod. Phys.* 75 (2003) 657–712. <https://doi.org/10.1103/RevModPhys.75.657>.
- [31] B.J. Powell, R.H. McKenzie, Quantum frustration in organic Mott insulators: from spin liquids to unconventional superconductors, *Rep. Prog. Phys.* 74 (2011) 056501. <https://doi.org/10.1088/0034-4885/74/5/056501>.
- [32] D.P. Arovas, E. Berg, S.A. Kivelson, S. Raghu, The Hubbard Model, *Annu. Rev. Condens. Matter Phys.* 13 (2022) 239–274. <https://doi.org/10.1146/annurev-conmatphys-031620-102024>.
- [33] P.W. Anderson, Localized Magnetic States in Metals, *Phys. Rev.* 124 (1961) 41–53. <https://doi.org/10.1103/PhysRev.124.41>.
- [34] K. Held, Electronic structure calculations using dynamical mean field theory, *Advances in Physics* 56 (2007) 829–926. <https://doi.org/10.1080/00018730701619647>.
- [35] Paras, K. Yadav, P. Kumar, D.R. Teja, S. Chakraborty, M. Chakraborty, S.S. Mohapatra, A. Sahoo, M.M.C. Chou, C.-T. Liang, D.-R. Hang, A Review on Low-Dimensional Nanomaterials: Nanofabrication, Characterization and Applications, *Nanomaterials* 13 (2022) 160. <https://doi.org/10.3390/nano13010160>.
- [36] K.S. Novoselov, A.K. Geim, S.V. Morozov, D. Jiang, Y. Zhang, S.V. Dubonos, I.V. Grigorieva, A.A. Firsov, Electric Field Effect in Atomically Thin Carbon Films, *Science* 306 (2004) 666–669. <https://doi.org/10.1126/science.1102896>.
- [37] Q.H. Wang, K. Kalantar-Zadeh, A. Kis, J.N. Coleman, M.S. Strano, Electronics and optoelectronics of two-dimensional transition metal dichalcogenides, *Nature Nanotech* 7 (2012) 699–712. <https://doi.org/10.1038/nnano.2012.193>.
- [38] C.R. Dean, A.F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, K.L. Shepard, J. Hone, Boron nitride substrates for high-quality graphene electronics, *Nature Nanotech* 5 (2010) 722–726. <https://doi.org/10.1038/nnano.2010.172>.
- [39] S. Iijima, Helical microtubules of graphitic carbon, *Nature* 354 (1991) 56–58. <https://doi.org/10.1038/354056a0>.
- [40] R.C. Ashoori, Electrons in artificial atoms, *Nature* 379 (1996) 413–419. <https://doi.org/10.1038/379413a0>.
- [41] Y. Aharonov, D. Bohm, Significance of Electromagnetic Potentials in the Quantum Theory, *Phys. Rev.* 115 (1959) 485–491. <https://doi.org/10.1103/PhysRev.115.485>.
- [42] D. Goldhaber-Gordon, H. Shtrikman, D. Mahalu, D. Abusch-Magder, U. Meirav, M.A. Kastner, Kondo effect in a single-electron transistor, *Nature* 391 (1998) 156–159. <https://doi.org/10.1038/34373>.

- [43] K.V. Klitzing, G. Dorda, M. Pepper, New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance, *Phys. Rev. Lett.* 45 (1980) 494–497. <https://doi.org/10.1103/PhysRevLett.45.494>.
- [44] M. König, S. Wiedmann, C. Brüne, A. Roth, H. Buhmann, L.W. Molenkamp, X.-L. Qi, S.-C. Zhang, Quantum Spin Hall Insulator State in HgTe Quantum Wells, *Science* 318 (2007) 766–770. <https://doi.org/10.1126/science.1148047>.
- [45] D. Loss, D.P. DiVincenzo, Quantum computation with quantum dots, *Phys. Rev. A* 57 (1998) 120–126. <https://doi.org/10.1103/PhysRevA.57.120>.
- [46] Q.H. Wang, K. Kalantar-Zadeh, A. Kis, J.N. Coleman, M.S. Strano, Electronics and optoelectronics of two-dimensional transition metal dichalcogenides, *Nature Nanotech* 7 (2012) 699–712. <https://doi.org/10.1038/nnano.2012.193>.
- [47] A.K. Geim, I.V. Grigorieva, Van der Waals heterostructures, *Nature* 499 (2013) 419–425. <https://doi.org/10.1038/nature12385>.
- [48] A. Gadomski, N. Kruszewska, Matter-Aggregating Low-Dimensional Nanostructures at the Edge of the Classical vs. Quantum Realm, *Entropy* 25 (2022) 1. <https://doi.org/10.3390/e25010001>.
- [49] M. Sato, Y. Ando, Topological superconductors: a review, *Rep. Prog. Phys.* 80 (2017) 076501. <https://doi.org/10.1088/1361-6633/aa6ac7>.
- [50] S.-B. Zhang, W.B. Rui, A. Calzona, S.-J. Choi, A.P. Schnyder, B. Trauzettel, Topological and holonomic quantum computation based on second-order topological superconductors, *Phys. Rev. Research* 2 (2020) 043025. <https://doi.org/10.1103/PhysRevResearch.2.043025>.
- [51] A.Y. Kitaev, Unpaired Majorana fermions in quantum wires, *Phys.-Usp.* 44 (2001) 131–136. <https://doi.org/10.1070/1063-7869/44/10S/S29>.
- [52] B.-J. Yang, M. Saeed Bahramy, N. Nagaosa, Topological protection of bound states against the hybridization, *Nat Commun* 4 (2013) 1524. <https://doi.org/10.1038/ncomms2524>.
- [53] S. Sachdev, *Quantum Phase Transitions*, 2nd ed., Cambridge University Press, 2011. <https://doi.org/10.1017/CBO9780511973765>.
- [54] T. Senthil, A. Vishwanath, L. Balents, S. Sachdev, M.P.A. Fisher, Deconfined Quantum Critical Points, *Science* 303 (2004) 1490–1494. <https://doi.org/10.1126/science.1091806>.
- [55] A. Miglio, V. Brousseau-Couture, E. Godbout, G. Antonius, Y.-H. Chan, S.G. Louie, M. Côté, M. Giantomassi, X. Gonze, Predominance of non-adiabatic effects in zero-point renormalization of the electronic band gap, *Npj Comput Mater* 6 (2020) 167. <https://doi.org/10.1038/s41524-020-00434-z>.
- [56] M. Rossi, P. Gasparotto, M. Ceriotti, Anharmonic and Quantum Fluctuations in Molecular Crystals: A First-Principles Study of the Stability of Paracetamol, *Phys. Rev. Lett.* 117 (2016) 115702. <https://doi.org/10.1103/PhysRevLett.117.115702>.
- [57] B. Richard, R. Boll, S. Banerjee, J.M. Schäfer, Z. Jurek, G. Kastirke, K. Fehre, M.S. Schöffler, N. Anders, T.M. Baumann, S. Eckart, B. Erk, A. De Fanis, R. Dörner, S. Grundmann, P. Grychtol, M. Hofmann, M. Ilchen, M. Kircher, K. Kubicek, M. Kunitski, X. Li, T. Mazza, S. Meister, N. Melzer, J. Montano, V. Music, Y. Ovcharenko, C. Passow, A. Pier, N. Rennhack, J. Rist, D.E. Rivas, D. Rolles, I. Schlichting, L.Ph.H. Schmidt, P. Schmidt, D. Trabert, F. Trinter, R. Wagner, P. Walter, P. Ziolkowski, A. Rudenko, M. Meyer, R. Santra, L. Inhester, T. Jahnke, Imaging collective quantum fluctuations of the structure of a complex molecule, *Science* 389 (2025) 650–654. <https://doi.org/10.1126/science.adu2637>.
- [58] I. Garate, Phonon-Induced Topological Transitions and Crossovers in Dirac Materials, *Phys. Rev. Lett.* 110 (2013) 046402. <https://doi.org/10.1103/PhysRevLett.110.046402>.
- [59] A. Georges, G. Kotliar, W. Krauth, M.J. Rozenberg, Dynamical mean-field theory of strongly correlated fermion systems and the limit of infinite dimensions, *Rev. Mod. Phys.* 68 (1996) 13–125. <https://doi.org/10.1103/RevModPhys.68.13>.
- [60] E. Dagotto, Complexity in Strongly Correlated Electronic Systems, *Science* 309 (2005) 257–262. <https://doi.org/10.1126/science.1107559>.

- [61] T. Brückel, Forschungszentrum Jülich, eds., Neutron scattering: lectures of the JCNS laboratory course held at Forschungszentrum Jülich and the research reactor FRM II of TU Munich in cooperation with RWTH Aachen and University of Münster, Forschungszentrum Jülich, Jülich, 2012.
- [62] H.C. Po, L. Zou, A. Vishwanath, T. Senthil, Origin of Mott Insulating Behavior and Superconductivity in Twisted Bilayer Graphene, *Phys. Rev. X* 8 (2018) 031089. <https://doi.org/10.1103/PhysRevX.8.031089>.
- [63] G.R. Stewart, Heavy-fermion systems, *Rev. Mod. Phys.* 56 (1984) 755–787. <https://doi.org/10.1103/RevModPhys.56.755>.
- [64] R. Comin, A. Damascelli, Resonant X-Ray Scattering Studies of Charge Order in Cuprates, *Annu. Rev. Condens. Matter Phys.* 7 (2016) 369–405. <https://doi.org/10.1146/annurev-conmatphys-031115-011401>.
- [65] M.B. Maple, C.L. Seaman, D.A. Gajewski, Y. Dalichaouch, V.B. Barbetta, M.C. De Andrade, H.A. Mook, H.G. Lukefahr, O.O. Bernal, D.E. MacLaughlin, Non fermi liquid behavior in strongly correlated f-electron materials, *J Low Temp Phys* 95 (1994) 225–243. <https://doi.org/10.1007/BF00754938>.
- [66] E. Morosan, D. Natelson, A.H. Nevidomskyy, Q. Si, Strongly Correlated Materials, *Advanced Materials* 24 (2012) 4896–4923. <https://doi.org/10.1002/adma.201202018>.
- [67] T. Isono, T. Terashima, K. Miyagawa, K. Kanoda, S. Uji, Quantum criticality in an organic spin-liquid insulator κ -(BEDT-TTF) $_2$ Cu $_2$ (CN) $_3$, *Nat Commun* 7 (2016) 13494. <https://doi.org/10.1038/ncomms13494>.
- [68] P. Gegenwart, Q. Si, F. Steglich, Quantum criticality in heavy-fermion metals, *Nature Phys* 4 (2008) 186–197. <https://doi.org/10.1038/nphys892>.
- [69] DG85, English: Phase diagram of a second order quantum phase transition, n.d. <https://commons.wikimedia.org/wiki/File:QuantumPhaseTransition.png> (accessed September 17, 2025).
- [70] M.V. Zimmermann, C.S. Nelson, J.P. Hill, D. Gibbs, M. Blume, D. Casa, B. Keimer, Y. Murakami, C.-C. Kao, C. Venkataraman, T. Gog, Y. Tomioka, Y. Tokura, X-ray resonant scattering studies of orbital and charge ordering in Pr $1-x$ Ca x MnO $_3$, *Phys. Rev. B* 64 (2001) 195133. <https://doi.org/10.1103/PhysRevB.64.195133>.
- [71] G.L. Squires, Introduction to the theory of thermal neutron scattering, 3rd ed, Cambridge university press, Cambridge, 2012.
- [72] L. Savary, L. Balents, Quantum spin liquids: a review, *Rep. Prog. Phys.* 80 (2017) 016502. <https://doi.org/10.1088/0034-4885/80/1/016502>.
- [73] A.R. Smith, Atomic-Scale Spin-Polarized Scanning Tunneling Microscopy and Atomic Force Microscopy: A Review, *Journal of Scanning Probe Microscopy* 1 (2006) 3–20. <https://doi.org/10.1166/jspm.2006.003>.
- [74] B. Jäck, Y. Xie, A. Yazdani, Detecting and Distinguishing Majorana Zero Modes with the Scanning Tunneling Microscope, (2021). <https://doi.org/10.48550/ARXIV.2103.13210>.
- [75] J. Alexander, S. Belikov, S. Magonov, AFM-Based Characterization of Electrical Properties of Materials, in: Y.L. Lyubchenko (Ed.), *Nanoscale Imaging*, Springer New York, New York, NY, 2018: pp. 99–127. https://doi.org/10.1007/978-1-4939-8591-3_7.
- [76] D. Lu, I.M. Vishik, M. Yi, Y. Chen, R.G. Moore, Z.-X. Shen, Angle-Resolved Photoemission Studies of Quantum Materials, *Annu. Rev. Condens. Matter Phys.* 3 (2012) 129–167. <https://doi.org/10.1146/annurev-conmatphys-020911-125027>.
- [77] E.D. Linnik, A.S. Mikheykin, D. Rubi, V.B. Shirokov, D. Mezzane, S.V. Kondovych, I.A. Lukyanchuk, A.G. Razumnaya, Raman Response of Quantum Critical Ferroelectric Pb-Doped SrTiO $_3$, *Crystals* 11 (2021) 1469. <https://doi.org/10.3390/cryst11121469>.
- [78] E. Kermarrec, A. Zorko, F. Bert, R.H. Colman, B. Koteswararao, F. Bouquet, P. Bonville, A. Hillier, A. Amato, J. Van Tol, A. Ozarowski, A.S. Wills, P. Mendels, Spin dynamics and disorder

- effects in the $S = 1/2$ Kagome Heisenberg spin-liquid phase of kagellite, *Phys. Rev. B* 90 (2014) 205103. <https://doi.org/10.1103/PhysRevB.90.205103>.
- [79] A.R. Wright, R.H. McKenzie, Quantum oscillations and Berry's phase in topological insulator surface states with broken particle-hole symmetry, *Phys. Rev. B* 87 (2013) 085411. <https://doi.org/10.1103/PhysRevB.87.085411>.
- [80] J.-N. Fuchs, F. Piéchon, G. Montambaux, Landau levels, response functions and magnetic oscillations from a generalized Onsager relation, *SciPost Phys.* 4 (2018) 024. <https://doi.org/10.21468/SciPostPhys.4.5.024>.
- [81] Y. Tian, X. Kong, L. Li, B. Zhang, W.-J. Gong, Quantized anomalous Hall conductivity induced by Floquet and strain engineering in second-order topological insulators, *Phys. Rev. B* 111 (2025) 235406. <https://doi.org/10.1103/PhysRevB.111.235406>.
- [82] C.-Z. Chang, C.-X. Liu, A.H. MacDonald, *Colloquium*: Quantum anomalous Hall effect, *Rev. Mod. Phys.* 95 (2023) 011002. <https://doi.org/10.1103/RevModPhys.95.011002>.
- [83] J. Orenstein, Ultrafast spectroscopy of quantum materials, *Physics Today* 65 (2012) 44–50. <https://doi.org/10.1063/PT.3.1717>.
- [84] E.B. Amuah, A.S. Johnson, S.E. Wall, An achromatic pump–probe setup for broadband, few-cycle ultrafast spectroscopy in quantum materials, *Review of Scientific Instruments* 92 (2021) 103003. <https://doi.org/10.1063/5.0066760>.
- [85] C. Giannetti, M. Capone, D. Fausti, M. Fabrizio, F. Parmigiani, D. Mihailovic, Ultrafast optical spectroscopy of strongly correlated materials and high-temperature superconductors: a non-equilibrium approach, *Advances in Physics* 65 (2016) 58–238. <https://doi.org/10.1080/00018732.2016.1194044>.
- [86] A. Kirilyuk, A.V. Kimel, T. Rasing, Ultrafast optical manipulation of magnetic order, *Rev. Mod. Phys.* 82 (2010) 2731–2784. <https://doi.org/10.1103/RevModPhys.82.2731>.
- [87] A. Zong, B.R. Nebgen, S.-C. Lin, J.A. Spies, M. Zuerch, Emerging ultrafast techniques for studying quantum materials, *Nat Rev Mater* 8 (2023) 224–240. <https://doi.org/10.1038/s41578-022-00530-0>.
- [88] R. Hanson, D.D. Awschalom, Coherent manipulation of single spins in semiconductors, *Nature* 453 (2008) 1043–1049. <https://doi.org/10.1038/nature07129>.
- [89] N.P. De Leon, K.M. Itoh, D. Kim, K.K. Mehta, T.E. Northup, H. Paik, B.S. Palmer, N. Samarth, S. Sangtawesin, D.W. Steuerman, Materials challenges and opportunities for quantum computing hardware, *Science* 372 (2021) eabb2823. <https://doi.org/10.1126/science.abb2823>.
- [90] R.K. Goyal, S. Maharaj, P. Kumar, M. Chandrasekhar, Exploring quantum materials and applications: a review, *J Mater. Sci: Mater Eng.* 20 (2025) 4. <https://doi.org/10.1186/s40712-024-00202-7>.
- [91] A.W. Elshaari, W. Pernice, K. Srinivasan, O. Benson, V. Zwiller, Hybrid integrated quantum photonic circuits, *Nat. Photonics* 14 (2020) 285–298. <https://doi.org/10.1038/s41566-020-0609-x>.
- [92] I. Sochnikov, D. Davino, B. Kalisky, dc SQUID Design with FemtoTesla Sensitivity for Quantum-Ready Readouts, *Phys. Rev. Applied* 14 (2020) 014020. <https://doi.org/10.1103/PhysRevApplied.14.014020>.
- [93] N.P. Armitage, E.J. Mele, A. Vishwanath, Weyl and Dirac semimetals in three-dimensional solids, *Rev. Mod. Phys.* 90 (2018) 015001. <https://doi.org/10.1103/RevModPhys.90.015001>.
- [94] L. Rondin, J.-P. Tetienne, T. Hingant, J.-F. Roch, P. Maletinsky, V. Jacques, Magnetometry with nitrogen-vacancy defects in diamond, *Rep. Prog. Phys.* 77 (2014) 056503. <https://doi.org/10.1088/0034-4885/77/5/056503>.
- [95] C.L. Degen, F. Reinhard, P. Cappellaro, Quantum sensing, *Rev. Mod. Phys.* 89 (2017) 035002. <https://doi.org/10.1103/RevModPhys.89.035002>.
- [96] L. Labonté, O. Alibert, V. D'Auria, F. Dautre, J. Etesse, G. Sauder, A. Martin, É. Picholle, S. Tanzilli, Integrated Photonics for Quantum Communications and Metrology, *PRX Quantum* 5 (2024) 010101. <https://doi.org/10.1103/PRXQuantum.5.010101>.

- [97] I. Žutić, J. Fabian, S. Das Sarma, Spintronics: Fundamentals and applications, *Rev. Mod. Phys.* 76 (2004) 323–410. <https://doi.org/10.1103/RevModPhys.76.323>.
- [98] Y. Deng, Y. Yu, Y. Song, J. Zhang, N.Z. Wang, Z. Sun, Y. Yi, Y.Z. Wu, S. Wu, J. Zhu, J. Wang, X.H. Chen, Y. Zhang, Gate-tunable room-temperature ferromagnetism in two-dimensional Fe₃GeTe₂, *Nature* 563 (2018) 94–99. <https://doi.org/10.1038/s41586-018-0626-9>.
- [99] K. Heshami, D.G. England, P.C. Humphreys, P.J. Bustard, V.M. Acosta, J. Nunn, B.J. Sussman, Quantum memories: emerging applications and recent advances, *Journal of Modern Optics* 63 (2016) 2005–2028. <https://doi.org/10.1080/09500340.2016.1148212>.
- [100] D. Larbalestier, A. Gurevich, D.M. Feldmann, A. Polyanskii, High-T_c superconducting materials for electric power applications, *Nature* 414 (2001) 368–377. <https://doi.org/10.1038/35104654>.
- [101] P. Schofield, A. Bradicich, R.M. Gurrola, Y. Zhang, T.D. Brown, M. Pharr, P.J. Shamberger, S. Banerjee, Harnessing the Metal–Insulator Transition of VO₂ in Neuromorphic Computing, *Advanced Materials* 35 (2023) 2205294. <https://doi.org/10.1002/adma.202205294>.
- [102] C. Tedesco, G. Giovilli, L. Malavasi, Photocatalytic Nitrogen Fixation Materials and Mechanistic Features: State of the Art and Future Perspectives, *Eur J Inorg Chem* 28 (2025) e202400686. <https://doi.org/10.1002/ejic.202400686>.
- [103] S.W. Oxandale, C. Reinke, S.R. Das, I. El-Kady, Enhanced thermoelectric performance via quantum confinement in a metal oxide semiconductor field effect transistor for thermal management, *Commun Mater* 4 (2023) 85. <https://doi.org/10.1038/s43246-023-00397-w>.
- [104] A. Ospanova, Y. Koshkinbayev, A. Kainarbay, T. Alibay, R. Daurenbekova, A. Akhmetova, A. Vinokurov, S. Bubenov, S. Dorofeev, D. Daurenbekov, Investigation of the Influence of Structure, Stoichiometry, and Synthesis Temperature on the Optical Properties of CdTe Nanoplatelets, *Nanomaterials* 14 (2024) 1814. <https://doi.org/10.3390/nano14221814>.
- [105] S. Franchi, G. Trevisi, L. Seravalli, P. Frigeri, Quantum dot nanostructures and molecular beam epitaxy, *Progress in Crystal Growth and Characterization of Materials* 47 (2003) 166–195. <https://doi.org/10.1016/j.pcrysgrow.2005.01.002>.
- [106] J.C. Nie, J.Y. Yang, Y. Piao, H. Li, Y. Sun, Q.M. Xue, C.M. Xiong, R.F. Dou, Q.Y. Tu, Quantum confinement effect in ZnO thin films grown by pulsed laser deposition, *Applied Physics Letters* 93 (2008) 173104. <https://doi.org/10.1063/1.3010376>.
- [107] L. Fan, M. Zhu, X. Lee, R. Zhang, K. Wang, J. Wei, M. Zhong, D. Wu, H. Zhu, Direct Synthesis of Graphene Quantum Dots by Chemical Vapor Deposition, *Part & Part Syst Charact* 30 (2013) 764–769. <https://doi.org/10.1002/ppsc.201300125>.
- [108] Q. Hao, H. Lv, H. Ma, X. Tang, M. Chen, Development of Self-Assembly Methods on Quantum Dots, *Materials* 16 (2023) 1317. <https://doi.org/10.3390/ma16031317>.
- [109] I.U. Arachchige, S.L. Brock, Sol–Gel Methods for the Assembly of Metal Chalcogenide Quantum Dots, *Acc. Chem. Res.* 40 (2007) 801–809. <https://doi.org/10.1021/ar600028s>.
- [110] Z. Ning, J. Qian, Y. Liu, F. Chen, M. Zhang, L. Deng, X. Yuan, Q. Ge, H. Jin, G. Zhang, W. Peng, S. Qiao, G. Mu, Y. Chen, W. Li, Coexistence of Ferromagnetism and Superconductivity at KTaO₃ Heterointerfaces, *Nano Lett.* 24 (2024) 7134–7141. <https://doi.org/10.1021/acs.nanolett.4c02500>.
- [111] J.-J. Zhang, S. Dong, Effect of Rashba spin-orbit coupling on topological phases in monolayer ZnIn₂Te₄, *Phys. Rev. B* 111 (2025) 235451. <https://doi.org/10.1103/dxz2-yj9b>.
- [112] Y. Han, M. Wu, C. Gui, C. Zhu, Z. Sun, M.-H. Zhao, A.A. Savina, A.M. Abakumov, B. Wang, F. Huang, L. He, J. Chen, Q. Huang, M. Croft, S. Ehrlich, S. Khalid, Z. Deng, C. Jin, C.P. Grams, J. Hemberger, X. Wang, J. Hong, U. Adem, M. Ye, S. Dong, M.-R. Li, Data-driven computational prediction and experimental realization of exotic perovskite-related polar magnets, *Npj Quantum Mater.* 5 (2020) 92. <https://doi.org/10.1038/s41535-020-00294-2>.
- [113] U. Schollwöck, The density-matrix renormalization group, *Rev. Mod. Phys.* 77 (2005) 259–315. <https://doi.org/10.1103/RevModPhys.77.259>.

- [114] Z.-X. Li, H. Yao, Sign-Problem-Free Fermionic Quantum Monte Carlo: Developments and Applications, *Annu. Rev. Condens. Matter Phys.* 10 (2019) 337–356. <https://doi.org/10.1146/annurev-conmatphys-033117-054307>.
- [115] M. Cerezo, G. Verdon, H.-Y. Huang, L. Cincio, P.J. Coles, Challenges and opportunities in quantum machine learning, *Nat Comput Sci* 2 (2022) 567–576. <https://doi.org/10.1038/s43588-022-00311-3>.
- [116] D. Aoki, J.-P. Brison, J. Flouquet, K. Ishida, G. Knebel, Y. Tokunaga, Y. Yanase, Unconventional superconductivity in UTe_2 , *J. Phys.: Condens. Matter* 34 (2022) 243002. <https://doi.org/10.1088/1361-648X/ac5863>.
- [117] J.A. Sobota, Y. He, Z.-X. Shen, Angle-resolved photoemission studies of quantum materials, *Rev. Mod. Phys.* 93 (2021) 025006. <https://doi.org/10.1103/RevModPhys.93.025006>.
- [118] A. Gali, A. Schleife, A.J. Heinrich, A. Laucht, B. Schuler, C. Chakraborty, C.P. Anderson, C. Déprez, J. McCallum, L.C. Bassett, M. Friesen, M.E. Flatté, P. Maurer, S.N. Coppersmith, T. Zhong, V. Begum-Hudde, Y. Ping, Challenges in advancing our understanding of atomic-like quantum systems: Theory and experiment, *MRS Bulletin* 49 (2024) 256–276. <https://doi.org/10.1557/s43577-023-00659-5>.
- [119] M. Cheng, R.M. Lutchyn, S. Das Sarma, Topological protection of Majorana qubits, *Phys. Rev. B* 85 (2012) 165124. <https://doi.org/10.1103/PhysRevB.85.165124>.
- [120] L. Postler, S. Heußen, I. Pogorelov, M. Rispler, T. Feldker, M. Meth, C.D. Marciniak, R. Stricker, M. Ringbauer, R. Blatt, P. Schindler, M. Müller, T. Monz, Demonstration of fault-tolerant universal quantum gate operations, (2021). <https://doi.org/10.48550/ARXIV.2111.12654>.
- [121] J. Verjauw, R. Acharya, J. Van Damme, Ts. Ivanov, D.P. Lozano, F.A. Mohiyaddin, D. Wan, J. Jussot, A.M. Vadiraj, M. Mongillo, M. Heyns, I. Radu, B. Govoreanu, A. Potočnik, Path toward manufacturable superconducting qubits with relaxation times exceeding 0.1 ms, *Npj Quantum Inf* 8 (2022) 93. <https://doi.org/10.1038/s41534-022-00600-9>.
- [122] Y. Xu, S. Liu, D.A. Rhodes, K. Watanabe, T. Taniguchi, J. Hone, V. Elser, K.F. Mak, J. Shan, Correlated insulating states at fractional fillings of moiré superlattices, *Nature* 587 (2020) 214–218. <https://doi.org/10.1038/s41586-020-2868-6>.