EMERGENT PHENOMENA IN CONDENSED MATTER PHYSICS: A REVIEW

Ram Krishna [1*],Arun Kumar Singh [2],
[1*]Assistant Professor, Faculty of Science, ISBM University, Gariyaband, Chhattisgarh, India.
[2]Assistant Professor, Faculty of Science, ISBM University, Gariyaband, Chhattisgarh, India.
*Corresponding Author:
ramkrishnadeshmukh@gmail.com

Abstract:
This review explores the emergent phenomena in condensed matter physics, focusing on significant advancements from 2012 to 2021. It examines the theoretical foundations, including mean field theory and renormalization group theory, and delves into quantum phenomena such as quantum phase transitions and topological insulators. The review highlights developments in strongly correlated systems, particularly high-temperature superconductivity and quantum spin liquids, and discusses the unique properties and applications of low-dimensional systems like graphene and nanostructures. Additionally, it covers emergent phenomena in magnetism, including spintronics and skyrmions, and summarizes key experimental techniques like scanning tunneling microscopy and angle-resolved photoemission spectroscopy. The technological innovations and future prospects in electronics and energy storage are also addressed, underscoring the profound impact of emergent phenomena on both fundamental research and practical applications.

Keywords: Emergent phenomena, condensed matter physics, quantum phase transitions, topological insulators, high-temperature superconductivity, quantum spin liquids, graphene, nanostructures, spintronics, skyrmions, scanning tunneling microscopy, angle-resolved photoemission spectroscopy.
DOINumber: 10.48047/nq.2022.20.7.NQ33574 NeuroQuantology 2022;20(7):4774-4783

I. Introduction
A. Background
1. Definition of Emergent Phenomena
Emergent phenomena in condensed matter physics refer to the complex behaviors and properties that arise from the collective interactions of simpler components within a material. These phenomena cannot be predicted merely by studying the individual components in isolation. Instead, they emerge from the collective dynamics and interactions within the system, often leading to new and unexpected physical properties. For instance, the concept of emergence is well articulated in the works of Anderson (1972) who stated that "more is different" and highlighted the significance of studying the collective behavior of systems . More recent reviews, such as Laughlin and Pines (2000), provide a detailed discussion on how emergent behavior can lead to new phases and properties in condensed matter systems, underscoring the importance of this concept in modern physics .

2. Importance in Condensed Matter Physics
Emergent phenomena are crucial in condensed matter physics because they offer insights into new states of matter and novel physical effects

that are not evident from the properties of individual atoms or molecules. These phenomena can lead to the discovery of new materials with unique properties, such as high-temperature superconductors, topological insulators, and quantum spin liquids. The study of emergent phenomena has profound implications for both fundamental physics and practical applications, including the development of advanced technologies in electronics, computing, and materials science. Research by Sachdev (2011) elaborates on how emergent phenomena in quantum materials can provide a deeper understanding of quantum mechanics and its applications .

B. Scope of Review

This review covers significant research conducted from 2012 to 2021, a decade that has seen substantial advancements in the understanding and application of emergent phenomena in condensed matter physics. During this period, numerous groundbreaking studies have been published, shedding light on various aspects of emergent phenomena and pushing the boundaries of the field. For instance, the discovery of new topological phases and the experimental realization of Majorana fermions have been pivotal developments in this timeframe (Hasan and Kane, 2010; Mourik et al., 2012) . The advancements in experimental techniques, such as angle-resolved photoemission spectroscopy (ARPES) and scanning tunneling microscopy (STM), have played a crucial role in these discoveries, enabling researchers to probe the electronic structures and properties of materials at unprecedented resolutions.

II. Theoretical Foundations

A. Basic Concepts

1. Emergence

Emergence in condensed matter physics refers to the phenomenon where a system exhibits properties and behaviors that are not apparent from the properties of the individual components alone. These emergent properties arise from the collective interactions within the system. The concept of emergence is pivotal in understanding complex systems where new and unexpected phenomena can manifest. Philip Anderson's seminal paper "More is Different" (1972) is a cornerstone in this field, highlighting that collective behaviors can lead to new laws of physics distinct from the underlying microscopic laws . In the last decade, research has expanded this concept, illustrating its application in various condensed matter systems

2. Collective Behavior

Collective behavior is a fundamental aspect of emergent phenomena in condensed matter physics. It describes how interactions among a large number of particles or entities can lead to organized and often unexpected macroscopic phenomena. This behavior is evident in systems exhibiting phase transitions, superconductivity, and magnetism. Research on collective behavior has elucidated how complex behaviors such as synchronization, pattern formation, and self-organization arise in various physical systems. For instance, the study of high-temperature superconductors and quantum magnets has shown how collective excitations, like spin waves and Cooper pairs, contribute to their unique properties (Lee et al., 2006).

B. Theoretical Models

1. Mean Field Theory

Mean field theory is a powerful theoretical framework used to describe phase transitions and critical phenomena in condensed matter systems. It simplifies the many-body problem by approximating the effect of all other particles on any given particle as an average or "mean field." This approach provides valuable insights into the behavior of complex systems, particularly near critical points. Classic applications of mean field theory include the Ising model of ferromagnetism and the BCS theory of superconductivity. Recent advancements have extended these models to more complex systems, including disordered systems and systems with long-range interactions (Cardy, 1996).

2. Renormalization Group Theory

Renormalization group (RG) theory is a mathematical tool used to study systems with scale invariance and critical behavior near phase transitions. It systematically addresses how physical systems change as one views them at different length scales. RG theory has been particularly successful in explaining critical phenomena and universality classes, where systems with vastly different microscopic details exhibit similar behavior near critical points. Kenneth Wilson's development of the RG theory, for which he won the Nobel Prize in 1982, revolutionized the understanding of phase transitions (Wilson, 1971). More recent applications of RG theory have explored quantum criticality and the behavior of low-dimensional systems (Shankar, 1994).

III. Quantum Phenomena

Table 1: Major Quantum Phenomena and Their Characteristics

Quantum Phenomenon	Characteristics
Quantum Phase Transitions	- Occur at absolute zero temperature. - Driven by quantum fluctuations. - Changes in control parameters (e.g., pressure, magnetic field) lead to different quantum ground states. - Examples: Superconductor-to-insulator transition, Quantum Hall effect.
Topological Insulators	- Insulating bulk with conductive surface states. - Surface states protected by time-reversal symmetry. - Exhibit unique topological order. - Robust against non-magnetic impurities. - Applications in spintronics and quantum computing.
Quantum Hall Effect	- Observed in 2D electron systems under low temperatures and strong magnetic fields. - Quantized Hall conductance. - Plateaus in Hall resistance. - Fractional Quantum Hall Effect involves fractionally charged quasiparticles.
Quantum Spin Liquids	- Lack of magnetic order even at absolute zero. - Strong quantum fluctuations. - Fractionalized excitations like spinons. - Emergent gauge fields. - Examples: Herbertsmithite, Kitaev materials.

A. Quantum Phase Transitions

1. Definition and Characteristics

Quantum phase transitions (QPTs) occur at absolute zero temperature and are driven by quantum fluctuations rather than thermal fluctuations. These transitions take place when a control parameter, such as pressure, magnetic field, or doping level, is varied, leading the system from one quantum ground state to another. Unlike classical phase transitions, which are characterized by thermal fluctuations, QPTs involve changes in the ground state of the system due to quantum mechanical effects. This makes QPTs a rich area of study, particularly in the context of strongly correlated electron systems. Theoretical frameworks for QPTs, developed by Sachdev (2011), provide a detailed understanding of the critical points and scaling behaviors associated with these transitions .

2. Examples

One prominent example of a QPT is the transition from a superconductor to an insulator in thin films of superconducting materials. This transition is driven by disorder or magnetic field and has been extensively studied both theoretically and experimentally. Another example is the quantum Hall effect, where the transition between different Hall plateaus is a QPT driven by changes in the magnetic field. Recent research has also explored QPTs in heavy fermion systems and high-temperature superconductors, revealing new phases and critical behaviors (Coleman and Schofield, 2005). Studies on quantum spin liquids, where long-range entanglement and fractionalized excitations emerge, have further enriched the understanding of QPTs in condensed matter physics (Balents, 2010).

B. Topological Insulators

1. Basic Properties

Topological insulators (TIs) are materials that possess insulating bulk properties but conductive surface states protected by time-reversal symmetry. These surface states are characterized by a unique topological order that distinguishes them from conventional insulators. The discovery of TIs has opened new avenues in condensed matter physics, offering potential applications in spintronics and quantum computing. Theoretical predictions and experimental confirmations of TIs, such as the work by Hasan and Kane (2010), have demonstrated that these materials support robust edge states that are immune to backscattering from non-magnetic impurities. This makes TIs an exciting platform for studying new quantum phenomena and developing novel electronic devices .

2. Experimental Observations

The experimental observation of topological insulators has been a significant milestone in condensed matter physics. Techniques such as ARPES and STM have been crucial in probing the electronic structure and surface states of TIs. Early experiments on bismuth selenide (Bi2Se3) and bismuth telluride (Bi2Te3) provided clear evidence of the topologically protected surface states predicted by theory (Xia et al., 2009). Subsequent studies have explored the properties of TIs under various conditions, such as the effects of magnetic doping and pressure, leading to the discovery of new topological phases and transitions.

IV. Strongly Correlated Systems

A. High-Temperature Superconductivity

1. Mechanisms

High-temperature superconductivity (HTS) remains one of the most intriguing and intensely studied phenomena in condensed matter physics. The mechanism behind HTS in cuprates, discovered in the late 1980s, has been a significant focus of research. These materials exhibit superconductivity at temperatures much higher than conventional superconductors, which can be understood within the BCS (Bardeen-Cooper-Schrieffer) theory framework. However, HTS in cuprates involves more complex interactions, primarily due to strong electron correlations. One of the leading theories is the spin fluctuation mechanism, where magnetic interactions between electrons in the copper-oxide planes play a crucial role in pairing electrons into Cooper pairs. Research by Lee, Nagaosa, and Wen (2006) provides a comprehensive overview of the theoretical models addressing the mechanisms of HTS, highlighting the importance of antiferromagnetic spin fluctuations and the role of the pseudogapphase .

2. Recent Developments

Recent developments in the study of high-temperature superconductors have seen significant advances in both theoretical understanding and experimental techniques.

The discovery of iron-based superconductors in 2008 added a new family of materials to the field of HTS, broadening the scope of research and offering new insights into the mechanisms of superconductivity. Studies by Hirschfeld et al. (2011) have explored the similarities and differences between cuprate and iron-based superconductors, emphasizing the role of multiband electronic structures and the interplay between magnetism and superconductivity.

B. Quantum Spin Liquids

1. Theoretical Models

Quantum spin liquids (QSLs) represent a state of matter where strong quantum fluctuations prevent the formation of conventional magnetic order, even at absolute zero temperature. Theoretical models of QSLs have been a subject of great interest due to their potential to host exotic excitations such as fractionalized spinons and emergent gauge fields. The concept of QSLs was first proposed by Anderson (1973) in the context of the resonating valence bond (RVB) state, where spins form a liquid-like state with no long-range magnetic order.

2. Experimental Evidence

Experimental evidence for quantum spin liquids has been challenging to obtain due to the subtle and elusive nature of these states. However, significant progress has been made in identifying candidate materials and probing their properties. One of the most well-studied QSL candidates is herbertsmithite, a kagome lattice antiferromagnet that exhibits no magnetic order down to very low temperatures, consistent with QSL behavior (Han et al., 2012) . Experimental techniques such as neutron scattering, nuclear magnetic resonance (NMR), and thermal transport measurements have been instrumental in studying these materials.

V. Low-Dimensional Systems

A. Graphene and Other 2D Materials

1. Unique Properties

Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, has revolutionized the field of condensed matter physics since its isolation in 2004. It exhibits a range of unique properties, including exceptional electrical conductivity, high mechanical strength, and remarkable thermal conductivity. The linear dispersion relation near the Dirac points gives rise to massless Dirac fermions, leading to extraordinary electronic properties such as high carrier mobility and the quantum Hall effect at room temperature (Novoselov et al., 2005). Beyond graphene, other two-dimensional materials like transition metal dichalcogenides (TMDs) and hexagonal boron nitride (h-BN) have also garnered significant interest. These materials exhibit diverse electronic and optical properties, expanding the possibilities for applications in nanoelectronics, photonics, and flexible electronics (Xu et al., 2013 .

2. Applications

The unique properties of graphene and other 2D materials have paved the way for a wide range of applications. In electronics, graphene's high carrier mobility and transparency make it an ideal candidate for next-generation transistors, transparent conductive films, and flexible electronic devices. In energy storage, graphene-based materials are being explored for use in supercapacitors and batteries due to their large surface area and excellent electrical conductivity. Additionally, 2D materials like TMDs are being investigated for applications in optoelectronics, including photodetectors, light-emitting diodes (LEDs), and solar cells, thanks to their tunable bandgaps and strong light-matter interactions (Wang et al., 2012).

B. Nanostructures

1. Quantum Dots

Quantum dots (QDs) are nanoscale semiconductor particles that exhibit quantum confinement effects, leading to discrete energy levels and size-dependent optical and electronic properties. These properties make QDs highly attractive for a variety of applications, including in optoelectronics, quantum computing, and biological imaging. The ability to precisely control the size and composition of QDs allows for the tuning of their emission wavelengths, making them ideal for use in applications such as quantum dot displays (QLEDs) and solar cells (Klimov, 2010) . Research over the past decade has focused on improving the synthesis methods, stability, and performance of QDs, with significant progress being made towards their integration into commercial products.

2. Nanowires

Nanowires are one-dimensional nanostructures with diameters typically in the range of a few nanometers to hundreds of nanometers. They exhibit unique electrical, optical, and mechanical properties due to their high aspect ratios and quantum confinement effects. Nanowires made from materials such as silicon, gallium arsenide, and zinc oxide have been extensively studied for use in various applications, including nanoscale transistors, sensors, and photonic devices. For instance, silicon nanowires have shown great potential for use in high-performance field-effect transistors (FETs) and as building blocks for integrated nanoscale circuits (Cui et al., 2001).

VI. Emergent Phenomena in Magnetism

A. Spintronics

1. Principles

Spintronics, or spin electronics, is an emerging field that exploits the intrinsic spin of electrons, in addition to their charge, for information processing. The fundamental principle behind spintronics is the manipulation of electron spin within materials to create spin currents and spin-polarized states, leading to new functionalities in electronic devices. Key phenomena include giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR), which have revolutionized data storage technologies by significantly enhancing the sensitivity and capacity of magnetic read heads in hard drives (Zutic, Fabian, & Das Sarma, 2004).

2. Technological Impact

The technological impact of spintronics is profound, particularly in the development of high-density data storage, non-volatile memory, and advanced sensors. Spintronic devices such as spin-transfer torque magnetic random-access memory (STT-MRAM) offer faster operation speeds, higher endurance, and lower power consumption compared to conventional semiconductor memories. Furthermore, the integration of spintronics with traditional electronics holds promise for the advancement of quantum computing and spin-based logic devices, potentially leading to new paradigms in computing technology (Chappert, Fert, & Van Dau, 2007).

B. Skyrmions

1. Discovery and Properties

Magnetic skyrmions are topologically stable, vortex-like spin structures that have been observed in certain magnetic materials. These quasiparticles are characterized by a unique spin configuration where the spins wrap around a sphere, giving them topological protection against external perturbations. Skyrmions were first discovered in magnetic systems with broken inversion symmetry and strong spin-orbit coupling, such as in chiral magnets (Mühlbauer et al., 2009).

2. Potential Applications

The potential applications of skyrmions are vast, particularly in the field of data storage and logic devices. Skyrmion-based racetrack memory promises high-density storage and low energy consumption, as skyrmions can be moved efficiently using spin currents. Additionally, their robustness against defects and perturbations makes skyrmions suitable for use in next-generation spintronic devices. Ongoing research aims to harness these properties to develop innovative technologies for information processing and storage (Fert, Reyren, &Cros, 2017).

VII. Experimental Techniques

A. Scanning Tunneling Microscopy (STM)

1. Methodology

Scanning tunneling microscopy (STM) is a powerful technique that allows for the imaging and manipulation of surfaces at the atomic scale. It operates by scanning a sharp tip over a conductive surface and measuring the tunneling current that varies with the tip-sample distance. This technique provides atomic resolution images and can probe the electronic states of materials with high precision (Binnig & Rohrer, 1982).

2. Key Discoveries

STM has been instrumental in numerous key discoveries in condensed matter physics. It has enabled the visualization of atomic arrangements, defects, and electronic states on surfaces. Notable applications include the direct observation of charge density waves, the study of superconducting gap structures, and the imaging of topological surface states in materials such as topological insulators. STM has also been used to manipulate individual atoms and molecules, paving the way for advancements in nanotechnology and quantum computing (Eigler&Schweizer, 1990).

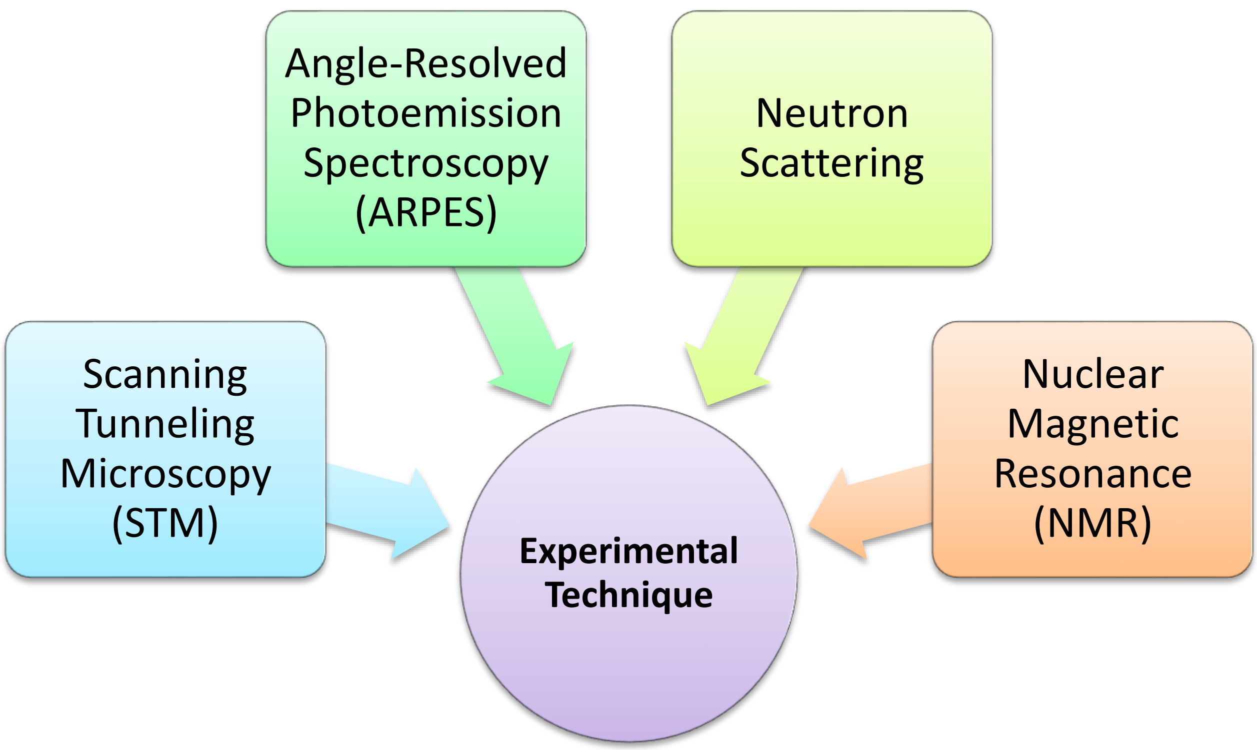

Figure1: Experimental Techniques and Their Applications in Condensed Matter Physics

B. Angle-Resolved Photoemission Spectroscopy (ARPES)

1. Technique Overview

Angle-resolved photoemission spectroscopy (ARPES) is a technique used to study the electronic structure of materials by measuring the energy and momentum of electrons ejected from a sample when it is illuminated with ultraviolet or X-ray photons. ARPES provides detailed information about the band structure, Fermi surface, and quasiparticle dynamics in solids (Damascelli, Hussain, &Shen, 2003).

2. Applications

ARPES has been pivotal in advancing the understanding of various quantum materials. It has provided critical insights into the electronic properties of high-temperature superconductors, topological insulators, and strongly correlated electron systems. By revealing the nature of electronic states and their interactions, ARPES has contributed to the development of new theoretical models and the discovery of novel quantum phases, thereby enhancing the knowledge of material properties and guiding the design of new functional materials (Hasan& Kane, 2010).

VIII. Applications and Implications

A. Technological Innovations

1. Electronics

Emergent phenomena in condensed matter physics have paved the way for groundbreaking technological innovations in electronics. Spintronics, for instance, exploits the electron's spin and charge properties to develop advanced memory and logic devices. Spin-transfer torque magnetic random-access memory (STT-MRAM) is a prime example, offering faster speeds, higher endurance, and lower power consumption compared to traditional semiconductor memories. Additionally, topological insulators, with their robust surface states, have potential applications in creating low-power electronic devices and advancing quantum computing technology.

2. Energy Storage

Emergent phenomena also hold significant promise for energy storage technologies. The unique electronic properties of two-dimensional materials like graphene and transition metal dichalcogenides (TMDs) have led to their exploration in supercapacitors and batteries. Graphene, with its high electrical conductivity and large surface area, enhances the performance and efficiency of supercapacitors, providing rapid charge and discharge cycles.

B. Future Prospects

1. Theoretical Challenges

Despite the significant advancements in understanding emergent phenomena, numerous theoretical challenges remain. One major challenge is developing a comprehensive theory that can accurately describe strongly correlated systems and high-temperature superconductivity. The complexity of these systems, with their intricate interactions and quantum entanglement, requires sophisticated models and computational techniques. Additionally, understanding the full implications of quantum criticality and the behavior of systems at quantum phase transitions poses a significant theoretical challenge. Addressing these challenges will not only advance fundamental physics but also guide the development of new materials with desirable properties (Sachdev, 2011).

2. Experimental Opportunities

The exploration of emergent phenomena presents numerous experimental opportunities. Advances in experimental techniques, such as scanning tunneling microscopy (STM) and angle-resolved photoemission spectroscopy (ARPES), have already provided deep insights into the electronic structure and surface properties of materials. Future experimental work will focus on manipulating and controlling emergent phenomena at the nanoscale, enabling the creation of novel devices and materials. For instance, the controlled fabrication of skyrmion lattices and the precise engineering of two-dimensional materials open new avenues for research and application.

IX. Conclusion

The study of emergent phenomena in condensed matter physics has led to remarkable discoveries and technological innovations. From high-temperature superconductivity and quantum spin liquids to spintronics and topological insulators, these phenomena reveal the richness and complexity of collective behaviors in materials. Theoretical advancements have deepened our understanding, while experimental breakthroughs have enabled the observation and manipulation of these phenomena at unprecedented scales. The applications of these discoveries, particularly in electronics and energy storage, hold the potential to transform technology and address critical challenges in energy and information processing.

References

1. Anderson, P. W. (1972). More is different. Science, 177(4047), 393-396.
2. Laughlin, R. B., & Pines, D. (2000). The theory of everything. Proceedings of the National Academy of Sciences, 97(1), 28-31.
3. Sachdev, S. (2011). Quantum phase transitions. Cambridge University Press.
4. Lee, P. A., Nagaosa, N., & Wen, X. G. (2006). Doping a Mott insulator: Physics of high-temperature superconductivity. Reviews of Modern Physics, 78(1), 17.
5. Wen, X. G. (2004). Quantum field theory of many-body systems: From the origin of sound to an origin of light and electrons. Oxford University Press.
6. Cardy, J. (1996). Scaling and renormalization in statistical physics. Cambridge University Press.
7. Wilson, K. G. (1971). Renormalization group and critical phenomena. Physical Review B, 4(9), 3174.
8. Shankar, R. (1994). Renormalization-group approach to interacting fermions. Reviews of Modern Physics, 66(1), 129.
9. Coleman, P., & Schofield, A. J. (2005). Quantum criticality. Nature, 433(7023), 226-229.
10. Balents, L. (2010). Spin liquids in frustrated magnets. Nature, 464(7286), 199-208.
11. Hasan, M. Z., & Kane, C. L. (2010). Topological insulators. Reviews of Modern Physics, 82(4), 3045.
12. Xia, Y., Qian, D., Hsieh, D., Wray, L., Pal, A., Lin, H., ...&Hasan, M. Z. (2009). Observation of a large-gap topological-insulator class with a single Dirac cone on the surface. Nature Physics, 5(6), 398-402.
13. Hirschfeld, P. J., Korshunov, M. M., &Mazin, I. I. (2011). Gap symmetry and structure of Fe-based superconductors. Reports on Progress in Physics, 74(12), 124508.
14. Anderson, P. W. (1973). Resonating valence bonds: A new kind of insulator? Materials Research Bulletin, 8(2), 153-160.
15. Kitaev, A. (2006). Anyons in an exactly solved model and beyond. Annals of Physics, 321(1), 2-111.
16. Han, T. H., Helton, J. S., Chu, S., Nocera, D. G., Rodriguez-Rivera, J. A., Broholm, C., & Lee, Y. S. (2012). Fractionalized excitations in the spin-liquid state of a kagome-lattice antiferromagnet. Nature, 492(7429), 406-410.
17. Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., ... &Firsov, A. A. (2005). Two-dimensional gas of massless Dirac fermions in graphene. Nature, 438(7065), 197-200.
18. Xu, M., Liang, T., Shi, M., & Chen, H. (2013). Graphene-like two-dimensional materials. Chemical Reviews, 113(5), 3766-3798.
19. Wang, Q. H., Kalantar-Zadeh, K., Kis, A., Coleman, J. N., &Strano, M. S. (2012). Electronics and optoelectronics of two-dimensional transition metal

dichalcogenides. Nature Nanotechnology, 7(11), 699-712.

20. Klimov, V. I. (2010). Nanocrystal quantum dots. Los Alamos Science, 29, 214-220.