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Editorial: Advancements and challenges in quantum technologies using low-dimensional systems

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Editorial on the Research Topic
Advancements and challenges in quantum technologies using low-dimensional systems

Background

The study of low-dimensional systems for quantum technologies has garnered significant attention in the past few years due to their potential in developing the next generation of quantum devices such as quantum batteries [1], sensors [2, 3], and quantum heat engines [4]. In this scenario, some materials like two-dimensional structures [5, 6], quantum dots [7], nanowires [8], and molecular magnetic systems [9, 10] offer distinctive platforms to study and utilize quantum phenomena [11, 12]. Recent advances have highlighted the potential of these low-dimensional quantum systems in developing more efficient quantum devices [1, 4, 13, 14]. These devices promise improvements in computational speed, sensing precision, and energy efficiency [2, 12]. Nevertheless, there are several challenges to overcome, including decoherence, noisy environments, and the difficulty of scaling quantum systems for real-world applications [15–17].

In this context, low-dimensional quantum materials are intriguing platforms providing opportunities for fundamental research. Therefore, to contextualize the advancements and challenges in this area, this Research Topic brings together different studies addressing some advancements, challenges, and directions in the research of quantum technologies that benefit from the useful features of low-dimensional systems.

Key contributions and insights

Each paper contributed original findings demonstrating innovative approaches to leveraging quantum technologies in various contexts.

Quantum magnetism in low-dimensional systems

Sivý et al. studied the magnetic properties of a molecular magnetic system $Fe_2 Cu_2$ with polymeric branched chains using an exactly solvable Ising–Heisenberg model. The findings advance the understanding of how quantum correlations can persist in advanced materials. Their results highlight the relationship between thermal fluctuations and quantum coherence, which could lead to novel designs for magnetic materials with tailored quantum properties.

Quantum thermodynamics and heat engines

In the same way, Rastegar-Sedehi and Cruz explored a low-dimensional interaction predominant in metal complexes systems to analyze the performance of a quantum Stirling heat engine. The model includes a two-particle Heisenberg model with Dzyaloshinskii–Moriya interaction. The study demonstrates how quantum features such as quantum entanglement can be used to enhance thermodynamic efficiency. These results not only expand the understanding of the performance of quantum thermodynamics devices, but also suggest practical applications in designing efficient quantum-based energy harvesting systems.

Quantum cryptography and secure communication

On the other hand, Hou et al. introduced a quantum computing application. The authors proposed a quantum private comparison protocol to solve the socialist millionaire problem, employing rotation operations and Bell states, ensuring robust security by preventing information leakage. The results depend on quantum features such as entanglement and Bell states. These features play a crucial role in utilizing low-dimensional systems as platforms for quantum information processing [18, 19]. Therefore, this highlights the potential for low-dimensional quantum systems to be applied in cryptographic applications.

Quantum machine learning and sensing

Following the quantum computing results, Dong et al. developed a hybrid (quantum-classical) neural network optimized with a quantum activation function. The proposed approach demonstrates how integrating quantum activation functions into machine learning models potentially enhances the performance across different predictive tasks. Therefore, the integration of quantum neural networks aligns well with the characterization of low-dimensional quantum systems, where local interactions and spatial correlations can play a significant role. In this regard, quantum energy devices, such as quantum heat engines based on low-dimensional systems, could benefit from these approaches, predicting their performance, and understanding energy fluctuations and the dynamics of their quantum correlations over time.

Quantum information security and image processing

On the other hand, Zeng et al. introduced a color watermarking algorithm utilizing the quantum discrete cosine transform and a sinusoidal-tent map. By using quantum features such as entanglement, the algorithm enhances resistance to tampering, addressing critical issues regarding digital content protection and intellectual property rights. In this regard, the efficient quantum operations proposed for this algorithm can provide insights into the manipulation of quantum states, which can be applied in the research of low-dimensional systems, with potential applications in future developments in quantum sensing and secure quantum communication protocols based on these systems.

Concluding remarks

The presented Research Topic highlighted the fundamental role of the study of low-dimensional quantum systems in advancing emerging quantum technologies. The papers cover from quantum magnetism and thermodynamics to practical applications in machine learning and information security. The collected works demonstrate how key quantum properties, such as entanglement and coherence, can be harnessed to improve quantum devices and protocols. The continued progress in this research area requires interdisciplinary efforts, focusing on themes related to scalability, noise mitigation, and integration with current classical technologies, making low-dimensional systems essential building blocks for next-generation quantum technologies.

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