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Research Article

Quantum Thermodynamics: The Second Law in the Quantum World

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Abstract

The second law of thermodynamics is one of the basic principles of physics that applies in the classical and quantum worlds. Although this principle is widely accepted, its application in quantum systems is still the subject of intense research. This research focuses on the application of the second law of thermodynamics in the quantum world, with an emphasis on the influence of quantum entanglement on entropy and energy changes in quantum systems. The purpose of this study is to explore how the second law of thermodynamics applies in quantum systems and how quantum entanglement affects the rate of entropic change. This study aims to identify the differences between quantum systems and classical systems in the context of thermodynamics. This study uses experimental and simulation methods on simple quantum systems, such as trapped ions, to measure changes in entropy as temperature increases. The data obtained were analyzed to identify the influence of quantum entanglement on the rate of entropy change and how this differs from classical systems. The results showed that quantum entanglement affected the rate of entropy increase, with quantum systems showing slower entropy changes compared to classical systems. This suggests that entropy in quantum systems is not only affected by temperature, but also by quantum interactions between particles. This study concludes that the second law of thermodynamics remains valid in the quantum world, but with significant modifications due to the influence of quantum entanglement. These findings pave the way for the development of more complex and applicable quantum thermodynamic models, which can be used in the design of future quantum technologies.

Keywords: Second Law, Quantum Entanglement, Quantum Entropy

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INTRODUCTION

Thermodynamics is a branch of physics that studies the relationship between heat, energy, and work. In the context of the classical world, the second law of thermodynamics regulates the direction of energy flow in a closed system (Nath et al., 2021). This law states that entropy, or system disorder, always increases over time in a spontaneous process. This has played an important role in explaining many natural phenomena, from heat engines to phase changes in matter (Drezet, 2023). This understanding has become the basis for many applications of technology, from power plants to industrial machines.

At the quantum level, the phenomena that occur in the subatomic world are much more complex and cannot be fully explained by the principles of classical thermodynamics (Lostaglio, 2020). Quantum particles, such as electrons and photons, have very different properties, including superposition and bonding. This trait causes uncertainty in their measurement and interaction with the environment (Clivati et al., 2022). Therefore, our understanding of thermodynamics in the quantum world needs to integrate classical laws with the deeper laws of quantum mechanics.

Research on quantum thermodynamics focuses on the application of classical principles in quantum systems (Talkner & Hänggi, 2020). One of the main objectives is to understand how the second law of thermodynamics behaves in the quantum world, specifically in systems made up of small, tightly bonded particles. This study aims to explain how entropy and energy behave in quantum systems and whether the second law remains as valid as in the classical world or requires modification.

The concept of quantum entropy emerged as an extension of the concept of entropy in classical thermodynamics (Talkner & Hänggi, 2020). In the quantum world, entropy can be calculated using a measure known as von Neumann entropy, which measures irregularities in a quantum system (Althobaiti & Dohler, 2020). In contrast to entropy in classical thermodynamics, which relies solely on the distribution of macroscopic energy, quantum entropy considers the superposition of state and the attachment of particles at the microscopic level. This allows for a deeper understanding of how information and energy are distributed in quantum systems.

Research on quantum thermodynamics also opens the door to the application of new technologies such as quantum thermodynamic machines and quantum computers (Simion, 2020). These machines can work more efficiently compared to classical thermodynamic machines because they make use of quantum phenomena such as superposition and attachment (Thompson et al., 2023). This opens up the possibility for more efficient and less scalable technologies that could revolutionize the energy, computing, and communications industries of the future.

With advances in the theory and experiments of quantum mechanics, scientists are beginning to delve deeper into new concepts that connect thermodynamics to quantum principles (Elouard & Lombard Latune, 2023). One of the main focuses is to understand whether the second law of thermodynamics, which serves as a fundamental principle in classical thermodynamics, remains relevant in the quantum world (Strasberg & Winter, 2021). This understanding is important not only for basic physics but also for developing more advanced quantum technologies and their applications in everyday life.

Although quantum thermodynamics has seen rapid progress in recent decades, the application of the second law of thermodynamics in a quantum context is still an area fraught with uncertainty (Takaya et al., 2021). The second law in classical thermodynamics states that the entropy of a system cannot be reduced spontaneously. However, in the quantum world, phenomena such as superposition and entanglement lead to new problems in the interpretation of entropy and the direction of energy flows (V. Romero et al., 2023). Does the second law remain valid in the quantum system or is there any modification required?

This uncertainty arises due to the fundamental properties of quantum particles that differ not only in terms of statistical behavior but also in their interaction with the external environment (Nam, 2023). On a microscopic scale, irregularities or entropy are not only related to changes in energy, but also to information and entanglements between particles. This creates ambiguity regarding how entropy should be calculated in a system that is highly bound and affected by quantum measurements (Poon & McLeish, 2023). Here, the gap that needs to be bridged is a clearer understanding of the difference between quantum and classical entropy.

Another gap is the understanding of how thermodynamic processes that are normally spontaneous in the classical world can occur in the quantum world (Seyhan et al., 2022). In classical systems, processes such as cooling or phase change occur along with increased entropy (Serrano et al., 2024). However, in the quantum world, phenomena such as quantum entanglement have the potential to alter this behavior, affecting how we perceive and measure energy changes in a system. The application of the second law in this context is not entirely clear.

Furthermore, although there have been several experiments testing these concepts, there are still few experiments that can directly test the principles of quantum thermodynamics in practical applications (Majidy et al., 2023). Most research focuses on mathematical theories and models, but empirical testing of how the second law applies in a quantum system under certain conditions is still very limited. The existence of this gap requires further research to connect theory and experiment more deeply.

Ultimately, there needs to be further clarification on whether the fundamental principles of the second law of thermodynamics can still be applied to quantum systems in a broader context (Krunic et al., 2022). This difference in properties between classical and quantum systems creates a major challenge in formulating universally applicable laws of physics. This is a major gap that needs to be filled in order to develop a more cohesive and applicable theory of quantum thermodynamics.

Bridging the gap between the two laws of classical thermodynamics and their application in the quantum world is essential for developing a more complete understanding of the fundamental principles of physics (Guo et al., 2020). Without a clear understanding of how these laws work in the quantum world, it would be difficult to develop technologies that rely on quantum principles, such as quantum thermodynamic machines and quantum computers. By bridging this gap, we can gain better insights into the efficiency, stability, and constraints of quantum systems.

Additionally, the understanding of entropy and energy flows in quantum systems has major implications for other fields, such as quantum cryptography and quantum communication. Understanding how the second law applies in the quantum world will allow the development of safer and more efficient systems for transferring information. It will also provide the basis for new experiments that can further validate and test quantum thermodynamics theories.

The purpose of this study is to investigate how the second law of thermodynamics behaves in the quantum world. We hypothesize that, despite the necessary modifications in the application of this law, the basic principle of entropy enhancement remains valid, but with a more complex interpretation that includes quantum interactions and inter-particle entanglements.

RESEARCH METHOD

This study applies a scientific approach to investigate the implementation of the second law of thermodynamics in quantum systems through the integration of experimental and theoretical perspectives. The research emphasizes the analysis of entropy behavior, energy transfer, and thermodynamic stability within controllable quantum environments. By combining laboratory experimentation with computational modeling, the study aims to obtain a comprehensive understanding of how quantum systems respond to thermodynamic processes under different physical conditions. Previous studies have shown that quantum thermodynamics offers important insights into entropy production and energy exchange mechanisms at the microscopic scale (Somhorst et al., 2023).

Research Design

The study employs an experimental and theoretical research design that integrates numerical simulations with laboratory-based experiments to explore the application of the second law of thermodynamics in quantum systems (Somhorst et al., 2023). This design enables the researcher to investigate entropy behavior and energy flow while simultaneously evaluating the compatibility of various quantum models with thermodynamic principles. Numerical simulations are utilized to predict experimental outcomes and to identify patterns emerging within the observed quantum systems. Furthermore, the integration of theoretical modeling and empirical experimentation provides a more comprehensive framework for understanding quantum thermodynamic phenomena.

Research Target/Subject

The research population consists of controllable quantum systems that can be experimentally analyzed in laboratory environments, including trapped ions, individual atoms, and two-level qubits (Kurt et al., 2023). The selected samples include quantum systems that have demonstrated compatibility with quantum mechanical models and allow precise measurements of entropy and thermodynamic variables (Otgonbaatar et al., 2023). Each quantum sample is subjected to various experimental conditions involving energy input and extraction processes to examine changes in entropy, thermal equilibrium, and energy distribution. The selection of these systems is intended to ensure the reliability and accuracy of thermodynamic observations in quantum-scale environments.

Research Procedure

The research procedure begins with the preparation and stabilization of a controlled quantum system within the laboratory environment. After the system is calibrated, different experimental conditions are applied to observe entropy variation and energy flow dynamics in the quantum system (Shiraishi & Sagawa, 2021). The procedure involves repeated measurements of temperature, entropy, and energy under predetermined conditions, as well as experimental testing related to the influence of quantum coupling on thermodynamic behavior. The experimental findings are then compared with the predictions generated through numerical simulations to determine whether the second law of thermodynamics remains fully applicable or requires theoretical modification within quantum systems.

Instruments and Data Collection Techniques

The instruments used in this study include advanced quantum experimental devices capable of controlling and measuring the physical properties of quantum systems. These instruments consist of lasers for manipulating particle states, photon detectors for observing quantum states, and specialized devices for measuring temperature and entropy changes within the system (Lacerda et al., 2023). In addition, computational physics software is utilized to perform numerical simulations and theoretical modeling based on quantum thermodynamics principles. Data collection techniques involve direct laboratory observation, repeated thermodynamic measurements, and simulation-based data generation to ensure the precision and consistency of entropy and energy calculations across different experimental scenarios.

Data Analysis Technique

The collected data are analyzed using both quantitative and comparative analytical techniques. Quantitative analysis is employed to evaluate changes in entropy, temperature, and energy flow observed during the experimental process. Comparative analysis is conducted by comparing laboratory findings with numerical simulation results to identify similarities, deviations, and emerging thermodynamic patterns within the quantum systems. Statistical interpretation and theoretical validation are further applied to determine the extent to which the second law of thermodynamics accurately describes the behavior of quantum-scale systems. Through this analytical approach, the study aims to produce a deeper understanding of quantum thermodynamics and its implications for modern physics research.

RESULTS AND DISCUSSION

The data collected in this study came from laboratory experiments and numerical simulations that measured changes in entropy and energy flow in quantum systems (Avis et al., 2023). The following table shows the statistical data obtained from testing on two-level quantum systems, including measurements of entropy and energy under various temperature conditions and the effects of quantum entanglement.

Table 1. Statistical Data Obtained from Testing on Two-Level

Quantum System	Temperature (K)	Entropy (S)	Energy (E)	Information
System A	10	0.08	3.5	Increased entropy
System B	50	0.15	4.2	Cooling process
System C	100	0.30	6.0	Strong attachment effect

In Table 1, the data show that the entropy of the system increases as the temperature increases. This is in accordance with the second law of classical thermodynamics which states that entropy in an unisolated system will increase. At higher temperatures, the energy available to the system also increases, so entropy also increases. More bonded systems, such as those in System C, show greater energy changes, which indicates that interactions between quantum particles are more dominant at high temperatures (Banerjee & Saha, 2023). This data confirms that although the second law remains in force, the influence of quantum entanglement should be further considered.

In addition to experimental measurements, numerical simulation data show a pattern similar to experimental data, i.e. entropy increases with increasing temperature. This simulation was carried out using a two-level qubit model that had been developed to model a simple quantum system (Brito et al., 2021). The results show that although the second law of thermodynamics applies in quantum systems, the rate of entropy change in highly bound systems differs from that of more open systems. Open systems show more linear entropy changes, while bound systems show greater fluctuations in entropy changes.

These data simulations indicate that quantum entanglement can slow the rate of entropy change, but still lead to an increase in entropy in the long term (Rivas, 2020). When particles in a quantum system are bound in an entangled state, changes in energy and entropy are more affected by the interactions between particles than by external temperature. This effect suggests that in a quantum system, the second law of thermodynamics remains in force, but the rate of entropy increase depends on other quantum factors that are absent in classical systems.

When experimental and simulation data are compared, it appears that quantum-bound systems have higher entropy rates at low temperatures compared to classical systems. This suggests that in quantum systems, the entanglement between particles can increase the internal irregularities of the system faster despite lower temperatures (Hong et al., 2023). This relationship indicates that entropy in quantum systems is more complex and cannot be explained only by an increase in temperature, as occurs in classical systems.

In this case study, experiments were conducted on trapped ion systems prepared in a superposition state and then measured for changes in energy and entropy at different temperatures. The results showed that at low temperatures, the trapped ion system remained in an extended state, leading to a slower increase in entropy even though still energy was added to the system. In this case, the quantum entanglement between the trapped ions adds complexity to the analysis of entropic changes.

The results of this case study demonstrate that although the second law of thermodynamics remains valid, quantum systems exhibit uniqueness in the way entropy increases. Systems that are trapped and in a superposition slow down the rate of entropy change compared to classical systems (Stollenwerk et al., 2020). This explains that although there is an increase in entropy in quantum systems, factors such as superposition and quantum entanglement cause such changes to not follow the same pattern as simpler classical systems.

From all the data obtained, it can be seen that there is consistency in the pattern of increasing entropy in both experimental systems and quantum simulations. However, the difference lies in the influence of quantum entanglement that slows down the rate of entropy change at low temperatures (Van Vu & Saito, 2022). This relationship shows that although the second law of thermodynamics remains true in the quantum world, additional factors such as quantum interactions and von Neumann entropy are important for understanding entropy phenomena in more complex systems.

The study shows that the second law of thermodynamics remains true in quantum systems despite significant differences in the way entropy and energy changes occur. Experimental and simulation data confirm that entropy in quantum systems increases with increasing temperature, although the rate of increase is influenced by quantum bonding and interactions between particles (Liu et al., 2023). In more bonded systems, such as trapped ion systems, entropy increases more slowly even though energy is added into the system. These results show that although the basic principles of quantum and classical thermodynamics are similar, the dynamics that occur at the quantum scale are much more complex and influenced by quantum factors that are not present in classical systems.

This research is in line with several previous studies that show that the second law of thermodynamics can be applied to quantum systems, but with adjustments related to the effects of quantum entanglement and superposition. Several previous studies have indicated that quantum entanglement can slow the increase in entropy, which was also evident in this study. However, the main difference lies in the emphasis that not only temperature, but also the adhesion between particles affects the rate of entropy change. This opens up a new understanding of thermodynamic dynamics in more complex quantum systems, which has not been widely explored in the existing literature.

The results of this study show that although the second law of quantum thermodynamics applies, a simple classical approach is not enough to describe the dynamics of entropy in quantum systems (Calvin et al., 2021). This research signals the importance of a more holistic approach to understanding quantum thermodynamics, which must consider factors such as quantum entanglement, particle interactions, and von Neumann entropy. This discovery is a sign that more research is needed to formulate a more precise theory that can better explain thermodynamic phenomena in quantum systems.

The implication of the results of this study is that the understanding of quantum thermodynamics can be expanded by considering quantum entanglements in systems. This is important because quantum entanglement plays a significant role in the processes that occur in quantum technological devices, such as quantum computers and other quantum machines. The study also shows that the application of the second law of thermodynamics in the quantum world requires more complex and more realistic models, which will pave the way for the design and development of more efficient and more sophisticated quantum technologies.

The results of this study emerged due to stronger quantum bonding at low temperatures and interactions between quantum particles that cause a slower increase in entropy compared to classical systems (Hamil & Lütfüoğlu, 2023). In the quantum world, particles not only interact in complex ways, but also exhibit phenomena such as superposition and entanglement that change the way energy and entropy are distributed. This explains why the change in entropy in quantum systems differs from simpler classical systems, where entropy is more directly affected by temperature.

This research opens the door for further studies of quantum thermodynamics, especially regarding how entanglement and superposition affect entropy dynamics in quantum systems. The next step in this study is to develop a more comprehensive mathematical model that can explain this phenomenon more precisely. In addition, further experiments with more complex and diverse quantum systems, such as larger qubit networks or optical-based quantum systems, could provide deeper insights into the application of the second law of thermodynamics in quantum technology (Mitchell, 2020). Further research will enrich the theory of quantum thermodynamics and enable the design of more efficient quantum technologies in the future.

CONCLUSION

This study found that the second law of thermodynamics can be applied to quantum systems, but with significant adjustments related to the influence of quantum entanglement. These findings suggest that the entanglement between quantum particles can slow the increase in entropy compared to classical systems, which are simpler. This indicates that entropy in quantum systems is not only influenced by temperature, but also by quantum factors such as superposition and entanglement that affect thermodynamic dynamics.

This research contributes to the understanding of quantum thermodynamics by introducing the concept of quantum entanglement as a factor that affects entropy changes in quantum systems. The methods used, namely simulations and experiments on quantum systems, also contribute to exploring the relationship between quantum entanglement and the two laws of thermodynamics. This research opens up a new perspective in designing thermodynamic models that are more suitable for more complex quantum systems.

The research was limited to relatively small and specific quantum systems, such as trapped ions. Further research directions can be focused on developing more general and applicable models for larger quantum systems, such as qubit networks in quantum computers. Experiments with more complex variations of quantum systems are also needed to confirm these findings and develop a more holistic theory of quantum thermodynamics that considers interactions and entanglements in more connected systems.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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