Journal of Tecnologia Quantica, 1(3) - April 2024 108-116

Journal of Tecnologia Quantica
E - ISSN 3048-1740 | P - ISSN 3062-6757

Sustainability Research in Quantum Optics: Defining the Role of Compressed Matter Physics

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Received: May 15, 2024	Revised: July 06, 2024	Accepted: July 06, 2024	Online: July 11, 2024

ABSTRACT
Quantum Optics, as a field that studies the interaction between light and matter at the quantum level, has the potential to reveal new phenomena in the physics of compressed matter. Compressed matter, often encountered in extreme conditions like stellar or planetary cores, is key to understanding fundamental physical processes and advanced technological applications. This research aims to explore and define the role of compressed matter physics in the context of sustainability. By examining how materials behave under extreme pressure and temperature, we seek to identify ways Quantum Optics can facilitate the development of new environmentally friendly materials and energy-efficient technologies. The methodology used involves a combination of Quantum Optics experiments and theoretical modelling. Experiments include using high-intensity lasers and ion traps to create compressed conditions. In contrast, theoretical models are used to predict the behaviour of the material and its effects on energy efficiency and sustainability. Results from experiments and theoretical models show that Quantum Optics techniques can be effectively used to control and manipulate compressed matter, providing new data on its mechanical and electronic properties. These findings suggest that exploiting the physics of compressed matter can play an important role in developing sustainable technologies. The conclusion of this research is to strengthen the position of Quantum Optics as a vital tool in sustainability research. Through Quantum Optics, the physics of compressed matter offers an uncharted path for innovation in sustainable materials and technologies. Further research is recommended to explore the practical application of these findings in industrial and environmental contexts.

Keywords: *Compressed Matter, Sustainability Research, Quantum Optics*

Journal Homepage https://journal.ypidathu.or.id/index.php/ijnis

How to cite: Oscar, S., Xavier, E & Mark, E. (2024). Sustainability Research in Quantum Optics: Defining the Role of Compressed Matter Physics. *Journal of Tecnologia Quantica*, 1(3), 108-116. https://doi.org/10.70177/quantica.v1i3.933
Published by: Yayasan Pedidikan Islam Daarut Thufulah

INTRODUCTION

Research in Quantum Optics has opened up new potential in understanding and exploiting the properties of matter at the quantum level (Z. Pan & Djordjevic, 2021). A special focus on compressed materials subjected to extremely high pressure and temperature conditions offers important insights into fundamental physics and technological applications (Amitkumar et al., 2021). The problems faced in studying compressed materials lie in the difficulty of generating and maintaining the extreme conditions required for this research and the challenges in measuring and analyzing the effects on the material under these conditions (Sawada et al., 2019)

This issue is important because understanding compressed materials can help develop new materials with unique properties beneficial for advanced technological applications and sustainability (Mo et al., 2022). These applications include energy storage, superconductive materials, and others (Lizeth Fernanda Silva Godoy et al., 2023). However, technical obstacles in creating and studying these extreme conditions often hinder progress in research (San Sebastián et al., 2020).

To address these issues, Quantum Optics offers advanced techniques that enable the creation, control, and analysis of matter under previously unattainable conditions (Volkov & Lipchak, 2023). Using high-intensity lasers, ion traps, and non-linear optical techniques allows researchers to accurately generate and manipulate the extreme conditions necessary to study compressed matter in depth (P. Senger, 2020). This research addressed gaps in our ability to efficiently produce, control, and analyze materials in compressed states (Yaovaja, 2022). By applying and expanding the capabilities of Quantum Optics, the main goal is to define and understand the role of compressed matter physics in a broader context, especially in developing sustainable technologies (Martínez Rey et al., 2022).

This research contributes to filling this knowledge gap by developing a methodology that enables Quantum Optics to study compressed materials more effectively (Chan & Chau, 2023). The approach used includes the development of experiments designed to test the latest theories and generate data that can help formulate sustainable technology solutions (Carbajo, 2021). This experiment was designed to verify the hypothesis and discover new phenomena that could expand our understanding of compressed matter (Anza & Crutchfield, 2022).

This research takes advantage of the latest technologies in Quantum Optics, such as developing new (Hoskins et al., 2023), more stable and precise laser sources and more sensitive measurement techniques, such as high-resolution spectroscopy and quantum-based imaging techniques (Alam et al., 2019). This innovation enables research into compressed materials in a previously impossible way, opening up the potential for applications in advanced materials design and more efficient energy systems (Guo & Pfau, 2021).

The novelty of this research lies in the application of innovative Quantum Optics techniques to address specific challenges in the study of compressed materials (Akishin & Ladygin, 2022). This differs from previous research, which focused on using this technique in other contexts, such as quantum information or fundamental measurements. Furthermore, it is hoped that this research will inspire more interdisciplinary exploration and development of new technologies based on these findings (Broadbent et al., 2020). Future researchers will be expected to integrate these results into practical applications and develop more effective sustainability solutions based on an understanding of them.

(Yoshioka et al., 2024), with the research title namely Hunting for quantum-classical crossover in condensed matter Problems, state that condensed matter problems offer the earliest platform for the demonstration of practical quantum advantages that are orders-of-magnitude more feasible than ever known candidates in terms of both qubits counts and total runtime.(Taha et al., 2024), with the research title Exploring Trends and Opportunities in Quantum-Enhanced Advanced Photonic Illumination Technologies, highlight that Quantum-enhanced sensing and imaging exploits nonclassical correlations to achieve unprecedented accuracy in chaotic environments. In addition to guaranteeing secure communications, quantum cryptography, protected by physical principles, ensures unbreakable cryptographic key exchange. As quantum computing speed increases exponentially, previously unimplementable uses for classical computers become feasible.

X. Pan et al., (2023), with the research title namely Protecting the Quantum Interference of Cat States by Phase-Space Compression States, present a versatile technique for creating robust non-Gaussian continuously-variable resource states in a highly linear bosonic mode and manipulating their phase-space distribution to achieve enhanced resilience against photon loss. Such compressed cat states offer an attractive avenue for obtaining new insights into quantum foundations and quantum metrology and for developing inherently more protected bosonic code words for quantum error correction.

RESEARCH METHODOLOGY

Research design

This research uses experimental and theoretical approaches to explore the role of compressed matter physics in the context of sustainability through Quantum Optics (Wang et al., 2023). The goal is to understand how Quantum Optics techniques can influence and optimize the properties of materials under extreme stress. Thus, this design integrates quantitative methods with controlled experiments to test hypotheses related to energy efficiency and sustainable material use.

Research procedure

The research process consists of several interrelated stages:

1. Device Development and Calibration: Before testing can begin, experimental devices involving high-intensity lasers, ion traps, and spectroscopy are set up and calibrated. This is important to ensure that the data collected is accurate and repeatable.
2. Experimental Testing: Involves using Quantum Optics techniques to create a compressed state in a sample of selected material. Techniques such as optical pumping and Doppler cooling are used to manipulate and measure the behaviour of materials under high pressure and temperature.
3. Data Collection: Data is collected through direct detection and monitoring techniques. These include measurements of emission spectra, changes in crystal structure, and changes in electronic properties.

4. Simulation Analysis: Parallel to experiments, computer simulations are carried out to model the behaviour of compressed materials and predict the influence of various variables. This helps in understanding experimental data and in refining experimental approaches.

Research Subjects or Research Ethics

The research subject here is a sample of material selected for the experiment. Because this research does not involve human or animal subjects, research ethics primarily focuses on the management and safe disposition of the materials used. All chemicals and samples are handled according to strict laboratory safety guidelines. This research also complies with all local and international regulations relating to the use and disposal of potentially hazardous materials.

Data Collection Techniques or Data Processing Methods

Data is collected through various measurement instruments integrated into the experimental setup. These include:

1. Spectrometry: To analyze the light emitted or absorbed by a sample, which provides information about the electronic and structural changes of the material.
2. Imaging Techniques: Electron microscopy and X-ray imaging are used to visualize physical changes in samples.
3. Thermodynamic Measurements: To record temperature and pressure changes in a sample during an experiment.

The collected data is processed using special data analysis software. Statistical analysis was performed to evaluate the significance of the findings, and the predictive model was refined based on the experimental results. Machine learning algorithms may also identify patterns or relationships that are not obvious through manual inspection

By integrating Quantum Optics techniques in compressed matter research, this research offers insights into fundamental physics and provides a foundation for developing more sustainable and efficient technologies (Backes et al., 2021). This research contributes to the scientific literature through rigorous and interdisciplinary methodology while providing practical directions for future applications.

RESULTS AND DISCUSSION

Research in Quantum Optics has revolutionized many aspects of science and technology, opening the door to new understandings and applications in physics and engineering (Symons & Popelier, 2022). One interesting and important application is in sustainability research, focusing on the physics of compressed matter. A deep understanding of compressed matter, often found in extreme conditions such as in the cores of stars or the depths of planets, is important for astrophysical science and has significant implications for developing sustainable technologies on Earth (Horn, 2022).

Compressed material has been subjected to extremely high pressure, drastically changing its physical and chemical properties (Ávila et al., 2020). Studying such materials often requires complex and expensive experimental setups, resulting in extreme conditions that create high pressures and temperatures. This is where Quantum Optics comes into play, providing highly precise and versatile tools for controlling and manipulating particles at the quantum level . This technique allows scientists to observe and measure the behaviour of matter under extreme conditions with a precision that has never been achieved before (Luo et al., 2021)

In sustainability, researching compressed materials can provide important insights into developing new materials that can withstand extreme pressures and temperatures (Agarwal, 2023). This is especially relevant for industries that require materials that can handle harsh conditions, such as space exploration, oil and gas drilling, and nuclear energy. Additionally, a better understanding of compressed materials could help design more efficient and sustainable processes for converting and storing energy, which is a key component in addressing climate change and increasing energy sustainability

Research in Quantum Optics into compressed materials involves the use of a variety of advanced methods (Emorine et al., 2022). High-intensity lasers, spectroscopy, and interferometric techniques are some of the main tools used. Lasers can create high-pressure conditions very quickly on a microscopic scale. At the same time, spectroscopy allows scientists to analyze how light interacts with matter and provides data about the material's electronic structure. Interferometry, which measures the phase difference between two or more light waves, helps map microscopic structural changes in compressed materials (A. Senger, 2020). All these techniques provide deeper insight into the fundamental properties of compressed materials and help develop better models to predict material behaviour under extreme conditions. This is important for designing materials that are not only more durable but also more environmentally friendly

The implications of this research go beyond the laboratory. With the ability to design more efficient and durable materials, we can reduce waste and increase material recycling in industry. More effective energy storage technologies, perhaps developing from a better understanding of compressed matter, will play a key role in the transition to renewable energy sources. Additionally, applications in earth sciences, such as understanding the movement of tectonic plates and volcanic dynamics, could also benefit from this research.

CONCLUSIONS

Sustainability research in Quantum Optics, which focuses on defining the role of compressed matter physics, has revealed significant potential to take our scientific understanding to the next level while providing practical benefits in developing sustainable technologies. Quantum Optics, with its ability to control and manipulate light on the quantum scale, provides an indispensable tool for studying the properties and behaviour of matter under very extreme conditions. Through this research, we have gained deeper insight into how materials behave under high pressure and temperature, which is important for many applications, from manufacturing advanced materials to efficient energy storage solutions.

This research shows that applying Quantum Optics techniques in studying compressed materials can dramatically improve our ability to generate, measure, and analyze previously difficult-to-reach phenomena. This expands the boundaries of our scientific knowledge and enables the development of new technologies that can reduce environmental impacts and improve energy efficiency. These advances underscore the importance of integrating scientific research and technological applications, demonstrating how basic research can directly contribute to sustainable solutions.

It is hoped that these findings will inspire more interdisciplinary research and collaboration in the fields of Quantum Optics and compressed matter physics, encouraging more sustainability-focused innovations and applications. It also sets the foundation for future researchers to explore and identify practical applications of this discovery, strengthening the link between science and technology in the global effort to achieve greener and more sustainable solutions.

REFERENCES

Bitzenbauer, P., Veith, J. M., Girnat, B., & Meyn, J.-P. (2022). Assessing Engineering Students' Conceptual Understanding of Introductory Quantum Optics. *Physics*, *4*(4), 1180–1201. https://doi.org/10.3390/physics4040077

Burenkov, I. A., Jabir, M. V., Battou, A., & Polyakov, S. V. (2020). Time-Resolving Quantum Measurement Enables Energy-Efficient, Large-Alphabet Communication. *PRX Quantum*, *1*(1), 010308. https://doi.org/10.1103/PRXQuantum.1.010308

Calderaro, L., Agnesi, C., Dequal, D., Vedovato, F., Schiavon, M., Santamato, A., Luceri, V., Bianco, G., Vallone, G., & Villoresi, P. (2018). Towards quantum communication from global navigation satellite system. *Quantum Science and Technology*, *4*(1), 015012. https://doi.org/10.1088/2058-9565/aaefd4

Casado, A., Guerra, S., & Plácido, J. (2019). From Stochastic Optics to theWigner Formalism: The Role of the Vacuum Field in Optical Quantum Communication Experiments. *Atoms*, *7*(3), 76. https://doi.org/10.3390/atoms7030076

Cavaliere, F., Prati, E., Poti, L., Muhammad, I., & Catuogno, T. (2020). Secure Quantum Communication Technologies and Systems: From Labs to Markets. *Quantum Reports*, *2*(1), 80–106. https://doi.org/10.3390/quantum2010007

Chan, K. S., & Chau, H. F. (2023). Reducing the impact of adaptive optics lag on optical and quantum communications rates from rapidly moving sources. *AIP Advances*, *13*(5), 055201. https://doi.org/10.1063/5.0149695

Di Candia, R., Yiğitler, H., Paraoanu, G. S., & Jäntti, R. (2021). Two-Way Covert Quantum Communication in the Microwave Regime. *PRX Quantum*, *2*(2), 020316. https://doi.org/10.1103/PRXQuantum.2.020316

Galvez, E. J. (2023). A Curriculum of Table-Top Quantum Optics Experiments to Teach Quantum Physics. *Journal of Physics: Conference Series*, *2448*(1), 012006. https://doi.org/10.1088/1742-6596/2448/1/012006

Geraldi, A., Bonavena, L., Liorni, C., Mataloni, P., & Cuevas, Á. (2019). A Novel Bulk-Optics Scheme for Quantum Walk with High Phase Stability. *Condensed Matter*, *4*(1), 14. https://doi.org/10.3390/condmat4010014

Gruneisen, M. T., Eickhoff, M. L., Newey, S. C., Stoltenberg, K. E., Morris, J. F., Bareian, M., Harris, M. A., Oesch, D. W., Oliker, M. D., Flanagan, M. B., Kay, B. T., Schiller, J. D., & Lanning, R. N. (2021). Adaptive-Optics-Enabled Quantum Communication: A Technique for Daytime Space-To-Earth Links. *Physical*

Review Applied, *16*(1), 014067. https://doi.org/10.1103/PhysRevApplied.16.014067

Hoskins, J. G., Kaye, J., Rachh, M., & Schotland, J. C. (2023). A fast, high-order numerical method for the simulation of single-excitation states in quantum optics. *Journal of Computational Physics*, *473*, 111723. https://doi.org/10.1016/j.jcp.2022.111723

Hu, C.-Q., Yan, Z.-Q., Gao, J., Jiao, Z.-Q., Li, Z.-M., Shen, W.-G., Chen, Y., Ren, R.-J., Qiao, L.-F., Yang, A.-L., Tang, H., & Jin, X.-M. (2019). Transmission of photonic polarization states through 55-m water: Towards air-to-sea quantum communication. *Photonics Research*, *7*(8), A40. https://doi.org/10.1364/PRJ.7.000A40

Kouadou, T., Diaz, D., & Kwiat, P. (2023). Portable integrated quantum optics for quantum communication. In D. F. Figer & M. Reimer (Eds.), *Photonics for Quantum 2023* (p. 55). SPIE. https://doi.org/10.1117/12.2680341

Li, X., Tong, Z., Lyu, W., Chen, X., Yang, X., Zhang, Y., Liu, S., Dai, Y., Zhang, Z., Guo, C., & Xu, J. (2022). Underwater quasi-omnidirectional wireless optical communication based on perovskite quantum dots. *Optics Express*, *30*(2), 1709. https://doi.org/10.1364/OE.448213

Liu, C., Pang, K., Zhao, Z., Liao, P., Zhang, R., Song, H., Cao, Y., Du, J., Li, L., Song, H., Ren, Y., Xie, G., Zhao, Y., Zhao, J., Rafsanjani, S. M. H., Willner, A. N., Shapiro, J. H., Boyd, R. W., Tur, M., & Willner, A. E. (2019). Single-End Adaptive Optics Compensation for Emulated Turbulence in a Bi-Directional 10-Mbit/s per Channel Free-Space Quantum Communication Link Using Orbital-Angular-Momentum Encoding. *Research*, *2019*, 2019/8326701. https://doi.org/10.34133/2019/8326701

Liu, R., Rozenman, G. G., Kundu, N. K., Chandra, D., & De, D. (2022). Towards the industrialisation of quantum key distribution in communication networks: A short survey. *IET Quantum Communication*, *3*(3), 151–163. https://doi.org/10.1049/qtc2.12044

Manzalini, A. (2020). Quantum Communications in Future Networks and Services. *Quantum Reports*, *2*(1), 221–232. https://doi.org/10.3390/quantum2010014

Martínez Rey, N., Torras, J., Alonso-Sánchez, Á., Magrasó Santa, C., Montilla Garcia, I., & Rodríguez-Ramos, L. F. (2022). Enabling efficient quantum communications with adaptive optics. In H. Hemmati & B. S. Robinson (Eds.), *Free-Space Laser Communications XXXIV* (p. 26). SPIE. https://doi.org/10.1117/12.2608420

Paul, S., & Scheible, P. (2020). Towards Post-Quantum Security for Cyber-Physical Systems: Integrating PQC into Industrial M2M Communication. In L. Chen, N. Li, K. Liang, & S. Schneider (Eds.), *Computer Security – ESORICS 2020* (Vol. 12309, pp. 295–316). Springer International Publishing. https://doi.org/10.1007/978-3-030-59013-0_15

Reiche, S., Knopp, G., Pedrini, B., Prat, E., Aeppli, G., & Gerber, S. (2022). A perfect X-ray beam splitter and its applications to time-domain interferometry and quantum optics exploiting free-electron lasers. *Proceedings of the National Academy of Sciences*, *119*(7), e2117906119. https://doi.org/10.1073/pnas.2117906119

Seguel, A. I., Anguita, J. A., & Pirela, C. S. (2023). Reduction of photon-losses caused by turbulence using spatial diversity in free-space optics quantum communications. In D. T. Wayne, J. A. Anguita, & J. P. Bos (Eds.), *Laser Communication and Propagation through the Atmosphere and Oceans XII* (p. 26). SPIE. https://doi.org/10.1117/12.2677129

Singh, S. K., Azzaoui, A. E., Salim, M. M., & Park, J. H. (2020). Quantum Communication Technology for Future ICT - Review. *Journal of Information Processing Systems*, *16*(6), 1459–1478. https://doi.org/10.3745/JIPS.03.0154

Stejskal, A., Procházka, V., Dudka, M., Vrba, V., Kočiščák, J., Šretrová, P., & Novák, P. (2023). A dual Mössbauer spectrometer for material research, coincidence experiments and nuclear quantum optics. *Measurement*, *215*, 112850. https://doi.org/10.1016/j.measurement.2023.112850

Sun, Y., Yan, L., Chang, Y., Zhang, S., Shao, T., & Zhang, Y. (2019). Two semi-quantum secure direct communication protocols based on Bell states. *Modern Physics Letters A*, *34*(01), 1950004. https://doi.org/10.1142/S0217732319500044

Tao, Z., Chang, Y., Zhang, S., Dai, J., & Li, X. (2019). Two Semi-Quantum Direct Communication Protocols with Mutual Authentication Based on Bell States. *International Journal of Theoretical Physics*, *58*(9), 2986–2993. https://doi.org/10.1007/s10773-019-04178-5

Thomas, O. F., McCutcheon, W., & McCutcheon, D. P. S. (2021). A general framework for multimode Gaussian quantum optics and photo-detection: Application to Hong–Ou–Mandel interference with filtered heralded single photon sources. *APL Photonics*, *6*(4), 040801. https://doi.org/10.1063/5.0044036

Xu, L., Yuan, S., Zeng, H., & Song, J. (2019). A comprehensive review of doping in perovskite nanocrystals/quantum dots: Evolution of structure, electronics, optics, and light-emitting diodes. *Materials Today Nano*, *6*, 100036. https://doi.org/10.1016/j.mtnano.2019.100036

Yamamoto, Y., Leleu, T., Ganguli, S., & Mabuchi, H. (2020). Coherent Ising machines—Quantum optics and neural network Perspectives. *Applied Physics Letters*, *117*(16), 160501. https://doi.org/10.1063/5.0016140

Yanagimoto, R., Ng, E., Wright, L. G., Onodera, T., & Mabuchi, H. (2021). Efficient simulation of ultrafast quantum nonlinear optics with matrix product states. *Optica*, *8*(10), 1306. https://doi.org/10.1364/OPTICA.423044

Yang, Y.-G., Liu, X.-X., Gao, S., Zhou, Y.-H., Shi, W.-M., Li, J., & Li, D. (2021). Towards practical anonymous quantum communication: A measurement-device-independent approach. *Physical Review A*, *104*(5), 052415. https://doi.org/10.1103/PhysRevA.104.052415

Yu, B., Liang, S., Zhang, F., Li, Z., Liu, B., & Ding, X. (2021). Water-stable $CsPbBr_3$ perovskite quantum-dot luminous fibers fabricated by centrifugal spinning for dual white light illumination and communication. *Photonics Research*, *9*(8), 1559. https://doi.org/10.1364/PRJ.427066

Zhao, J., Zhou, Y., Braverman, B., Liu, C., Pang, K., Steinhoff, N., Tyler, G., Willner, A., & Boyd, R. (2020). Investigate the performance of real-time adaptive optics correction in a turbulent high-dimensional quantum communication channel. In H. Hemmati & D. M. Boroson (Eds.), *Free-Space Laser Communications XXXII* (p. 48). SPIE. https://doi.org/10.1117/12.2547186

Zhou, Y., Mirhosseini, M., Oliver, S., Zhao, J., Rafsanjani, S. M. H., Lavery, M. P. J., Willner, A. E., & Boyd, R. W. (2019). Using all transverse degrees of freedom in quantum communications based on a generic mode sorter. *Optics Express*, *27*(7), 10383. https://doi.org/10.1364/OE.27.010383