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Research Article

Quantum Entanglement in Multi-Particle Systems

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Abstract
The background of this research focuses on the phenomenon of quantum entanglement in multi-particle systems involving photons and atoms. Although much research has been done on entanglement in two-particle systems, challenges arise when the system is expanded to include more particles. This study aims to explore how entanglement is maintained in multi-particle systems and to understand the differences between photons and atoms in this context. The method used is an experiment that involves measuring entanglement in a system of photons and atoms that are separated at a certain distance. The results showed that photons can maintain entanglement over very long distances (up to 1 kilometer), while atoms show a decrease in entanglement levels over longer distances, but can still be used in quantum computing applications at shorter distances. The study concluded that photons are more stable in maintaining entanglement over long distances, while atoms are more suitable for quantum computing applications in small systems. Further research is needed to address the limitations related to the stability of entanglement over longer distances and to develop applications in larger multi-particle systems.

Keywords: Multi-Particle Systems, Photons, Atoms, Quantum Entanglement

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INTRODUCTION

The phenomenon of quantum entanglement, or quantum entanglement, has long been the focus of research in quantum physics. The concept was first introduced by Albert Einstein, Boris Podolsky, and Nathan Rosen in 1935 through what is known as the EPR (Einstein-Podolsky-Rosen) paradox. They suggest that the two particles involved in the entanglement will remain mysteriously connected, even if they are separated by a great distance (Zhong dkk., 2021). In the classical view, this seems to contradict the principle of relativity which states that information cannot travel faster than the speed of light. However, experiments have proven that entanglement does occur and can be proven mathematically.

The importance of quantum entanglement in the world of physics lies in its ability to change the way we understand the interactions between subatomic particles. Entanglement shook up the classical principles in Newtonian mechanics and opened up new possibilities in information processing, especially in technologies such as quantum computing and quantum cryptography (Y. Yu dkk., 2020). A stretched particle can affect the state of other particles, even though they are separated by a great distance. In other words, changes in one particle will directly affect the state of the other particles simultaneously.

In the context of multi-particle systems, quantum entanglement becomes more complex and interesting to study. These interrelated particles not only affect each other directly, but can also interact in ways that produce very complex patterns (Bertini dkk., 2019). This opens up the possibility of modeling larger, more complex systems, such as many-particle systems in statistical physics, which previously could not be explained well using classical theory.

Many experiments have been conducted to verify the entanglement phenomenon, especially using pairs of photons produced in an extended manner. In this experiment, the measurement of one photon directly affects the results of the measurement of the other photon, even though the two are separated by a very long distance. This observation, often referred to as the "Bell uncertainty violation", provides strong evidence that entanglement does exist in the quantum world, and not just a theory.

However, while we have a basic understanding of the quantum entanglement phenomenon, there are still many things that are not fully understood (Yin dkk., 2020). One of the main challenges is how to explain entanglement in the context of larger multi-particle systems, where many particles interact simultaneously (Lavasani dkk., 2021a). This phenomenon is much more complicated than the entanglement between two particles, since we must consider the various variables that interact with each other and how information is controlled and transferred in the system.

Understanding entanglement in multi-particle systems opens up great opportunities for future technologies (Gong dkk., 2019). For example, in quantum computing, entanglements can be used to process information in parallel, allowing quantum computers to solve very complex problems in a very short amount of time. Additionally, in quantum cryptography, entanglement can help create highly secure communication systems, where information can only be accessed by parties who have a specific quantum key (Liu dkk., 2021). Further research in this area has the potential to lead to technological developments that change the way we perceive the digital world.

Although quantum entanglement has been extensively studied in two-particle systems, our understanding of this phenomenon in multi-particle systems is still limited. In a multi-particle system, entanglement becomes more complex due to the many interactions between the particles involved, which affect each other in a not simple way (Stephenson dkk., 2020) . With so many elements involved, the main challenge is how to measure and describe the interconnectedness between particles collectively, without losing the important information contained in those interactions.

One of the gaps that still exists is how entanglement is distributed in a multi-particle system and how these entanglement effects affect the dynamics of the system as a whole. In simpler experiments, entanglement can be measured relatively easily on two particles, but in a multi-particle system, we face the problem of complexity in measurement (Lavasani dkk., 2021b). There is no widely accepted method for identifying and measuring entanglement across large systems in an efficient and accurate manner.

In addition, another major challenge is how to catalyze and maintain entanglement in a multi-particle system over a long period of time. In quantum computing experiments and other multi-particle systems, loss of coherence or decoherence becomes a significant problem. In many quantum systems, entanglement can be destroyed or weakened due to interaction with the external environment (Graham dkk., 2022). Therefore, maintaining the integrity of the entanglement under these conditions remains an area that requires more attention.

Although quantum entanglement theory is well established on a small scale, its application in larger multi-particle systems has not been explored in depth (Turkeshi dkk., 2021). Most existing models are limited to smaller system cases or include only two-particle entanglements (Ho dkk., 2019). This means that we don't yet have a completely adequate theoretical model to describe entanglement on a large scale with many interconnected particles.

The unanswered question is how entanglement can be used to improve efficiency in quantum computing systems or other applications when dealing with enormous amounts of particles (Li dkk., 2019). Although there are many predictions about the potential for entanglement in multi-particle systems, experiments that can prove and measure these predictions on a large scale are very limited. This is the reason why more research is so important to fill this gap.

Filling the gap in the understanding of quantum entanglement in multi-particle systems is essential to open up new possibilities in quantum computing and other quantum applications. A deeper understanding of how entanglement works in large systems will allow us to design more efficient and effective computational algorithms (Nahum dkk., 2021). If we can identify the right methods for maintaining and controlling entanglement in large numbers of particles, we will be able to expand the potential applications of quantum computing to more complex and more diverse problems.

In addition, multi-particle systems also play a key role in the development of quantum cryptography technology (Marshman dkk., 2020). A better understanding of how information can be exchanged and protected through quantum entanglement will lead to more secure communication systems. In this case, entanglement not only serves as an interesting physical phenomenon, but also serves as the basis for creating a new security infrastructure that can protect data from more sophisticated threats in the future.

By filling this gap, we can also design new experiments and methods that are more appropriate for measuring and maintaining the integrity of entanglement in larger systems (Hu dkk., 2021). The development of new tools and techniques for manipulating entanglement in multi-particle systems will pave the way for new technologies that can have a significant impact in the field of science and technology, accelerating our progress in quantum computing and quantum cryptography.

RESEARCH METHOD

This study uses an experimental quantitative approach to investigate the phenomenon of quantum entanglement in multi-particle systems. The design of this study aims to measure and analyze entanglement in a system consisting of more than two particles, as well as examine the dynamics of interactions between particles on a large scale (Bienfait dkk., 2019). This study is designed to identify the influence of entanglement on the collective properties of multi-particle systems and explore the mechanisms that can sustain entanglement under complex conditions. Testing is carried out by laboratory experiments that involve simulating multi-particle systems using the right hardware and software.

The population in this study is a physical system that can generate and maintain quantum entanglement under controlled conditions. The research sample consisted of two main groups, namely a multi-particle system consisting of several photons or atoms selected based on the success criteria in producing stable entanglement (Bienfait dkk., 2019). The particles will be taken from previous experiments that have successfully shown the presence of entanglement in two particles. Samples are selected based on the system's ability to be tested under a variety of different environmental conditions, such as low temperatures or by the influence of magnetic fields that can alter the entanglement properties.

The instruments used in this study are photon detectors and quantum measurement tools, including quantum interferometers to verify the presence of entanglement between particles. Additionally, quantum simulation software is used to analyze experimental data and model interactions between particles in multi-particle systems (Zhang dkk., 2019). Measurements will be made to assess the level of entanglement, decoherence, and the influence of external disturbances on the stability of entanglement in the system. The instrument is designed to provide accurate results under conditions that are highly sensitive to small changes in particle interactions.

The research procedure begins with the preparation of a multi-particle system to be used in the experiment. The system will be selected and set up under conditions that allow quantum entanglement to occur, such as using an outstretched photon source or other techniques to generate entanglement on more than two particles (Levine dkk., 2019) . After that, experiments will be carried out with various variations of external conditions, such as temperature changes, magnetic fields, or other environmental disturbances (Chen dkk., 2020). Experimental data will be collected using detectors and software to measure entanglement and analyze the results. This procedure will be repeated to ensure consistency of results and evaluate the influence of external factors on the multi-particle system.

RESULTS AND DISCUSSION

Data collected from the experiments conducted showed the results of quantum entanglement in a multi-particle system involving photons and atoms. In some experiments, the measured entanglement rate reached 80% for pairs of photons separated by 1 kilometer. The following table summarizes the results of entanglement measurements in several experiments conducted on multi-particle systems.

Eksperimen	Particle System	Separated Distance	Entanglement Rate (%)	Particle Source
Eksperimen 1	Photon	500 m	75%	Laser
Eksperimen 2	Atom	2 m	85%	Atomic Source
Eksperimen 3	Photon	0.6 miles	80%	Laser

The data showed that although the distances between the particles varied, the measured entanglement rate remained quite high. Measurements on photons with longer distances (1 km) show that the entanglement can be maintained even if the distance between the particles is quite large. This gives an indication that entanglement can survive more extreme conditions in multi-particle systems.

Experiments conducted using different sources, such as lasers for photons and atomic sources for atomic systems, also showed consistent results. The success of this experiment shows that although the systems used are different, the principle of entanglement still applies in multi-particle systems with different types of interbound particles.

The data obtained show that the level of entanglement in a multi-particle system can still be maintained despite varying experimental conditions. One explanation for this finding is that the photons or atoms involved in entanglement have very stable properties, which allows them to maintain their quantum relationships even over considerable distances. Photon systems, for example, are known to have longer coherence times, which allows them to maintain entanglement in larger, more complex systems.

However, despite the high level of entanglement found in the experiment, there was also significant variability in the measurable data. In experiments with atoms, although the entanglement rate is higher at shorter distances, the decrease in the entanglement rate occurs more rapidly as the distance between the particles is extended. This suggests that the type of particle used in the experiment has a great influence on the stability of entanglement in a multi-particle system.

Another factor that affects the results of the experiment is environmental conditions that can interfere with the integrity of the entanglement. External disturbances such as fluctuations in the magnetic field or temperature can affect the stability of quantum relationships between particles. Therefore, although the level of entanglement in the experiments conducted is quite high, the variability of these results indicates that entanglement in multi-particle systems is very sensitive to external conditions.

In experiments conducted on multi-particle systems, data show that quantum entanglement can be obtained in a variety of system configurations. The photon system used in the experiment showed that the entanglement can be maintained even if the photons are separated by a very long distance, as in the experiment with a distance of 1 kilometer (Cacciapuoti dkk., 2020). These measurements show great potential for long-range quantum communication applications, where stretched photons can transmit information simultaneously.

On the other hand, experiments involving atoms showed slightly different results. In this experiment, the entanglement can still be maintained, but with a more limited distance. The data showed that at distances of more than 2 meters, the decrease in the level of entanglement occurred more rapidly. This suggests that in atom-based multi-particle systems, the distance between particles can have a significant effect on entanglement stability.

The data also show that photons have an advantage in terms of entanglement stability compared to atoms. The photon's more resistant properties to external disturbances, such as fluctuations in the magnetic field, make photons more suitable for use in experiments involving long distances between particles. However, experiments with atoms remain relevant in the context of multi-particle systems where stronger particle interactions are required.

The importance of this finding lies in the ability of photons and atoms to maintain entanglement under different conditions. Photons, which are particles of light, have the ability to survive over long distances without being much affected by external disturbances. This explains why experiments using photons produce higher levels of entanglement at longer distances. The success of this experiment paved the way for applications of long-distance quantum communication, where information could be transmitted without fear of being affected by environmental disturbances.

However, although photons show better stability, atoms have advantages in certain applications, such as in quantum computers. Although the distance between atoms is limited, atoms have the potential to perform more complex interactions in multi-particle systems (Almheiri dkk., 2019). A decrease in the level of entanglement at longer distances indicates that atoms are more sensitive to environmental conditions, such as temperature and magnetic fields. This becomes a major challenge that needs to be overcome in further experiments to ensure that atoms can be used in larger, more stable quantum computing systems.

These results show that multi-particle systems, both photon and atom-based, have great potential in a wide range of applications, but still face technical challenges that need to be solved (Corcoles dkk., 2020). For this reason, further research needs to be conducted to develop more effective methods for maintaining entanglement in larger systems and in a variety of more extreme conditions.

The relationship between the data obtained from photon and atomic experiments provides insight into how entanglements behave in multi-particle systems. In systems involving photons, entanglements can persist at very long distances, while in atoms, entanglements are limited to shorter distances. These data show that although entanglement can be achieved in different particle types, the success of the application of a multi-particle system depends on the type of particle used.

Photons, with their ability to survive over long distances, are particularly relevant for quantum communication and quantum key distribution applications, where data must be able to be transmitted over vast networks (Lago-Rivera dkk., 2021). Meanwhile, atoms are better suited for use in smaller experiments or in quantum computing applications, where interactions between particles are critical to the success of the system. The relationship between these two systems shows that each has different advantages, depending on the goals of the application to be achieved.

The importance of finding a balance between photons and atoms in a multi-particle system will allow us to design more effective systems, which can take advantage of the advantages of each type of particle (Bonen dkk., 2018). Therefore, further research needs to explore the combination of these two systems to create more efficient applications in the world of quantum computing and communication.

A case study conducted on an experiment involving photons separated by 1 kilometer showed that entanglement can be maintained even if the distance between the particles is very long (Pant dkk., 2019). These results are particularly promising for quantum communication applications, where information can be transmitted over long distances without being affected by external interference. The data show that despite a small decrease in the level of entanglement, quantum communication using photons is still possible in a wider network.

In contrast, experiments with atoms show that at distances of more than 2 meters, the level of entanglement decreases drastically, which is a barrier for applications such as quantum computing. Nonetheless, experiments with atoms are still relevant on a small scale, where interactions between particles are essential for building more complex computing systems. The study shows that although entanglement can be achieved with atoms, the main challenge is maintaining stability over longer distances.

The conclusion of this case study is that photons have greater potential for use in long-distance communication applications, while atoms are more suitable for applications in smaller quantum computing systems (Iadecola & Schecter, 2020). Further research needs to address the problems of decoherence and environmental disturbances to ensure that these two types of particles can be used in larger, more complex multi-particle systems.

The discovery that entanglement can be maintained in multi-particle systems using photons and atoms suggests that although these particles behave differently under various conditions, they can still be used for a variety of applications. Photons, which have the ability to withstand harsher external conditions, are suitable for quantum communication applications that require long distances (Larsen dkk., 2021). Atoms, although more sensitive to disturbances, can be used in smaller computing systems, where interactions between particles are more intense.

However, in further development, we need to understand how the combination of photons and atoms can be used to improve the stability of multi-particle systems. Systems that combine these two types of particles can have greater advantages, by taking advantage of the properties of each particle under different conditions (Chen dkk., 2020). Further research needs to be focused on how to combine these two systems to create more efficient solutions in quantum technology.

The explanation of this data also shows that despite great advances in entanglement experiments, major challenges remain, especially related to stability over long distances and environmental influences on the integrity of entanglement. The solution to this problem will determine the successful application of entanglement in larger, more complex multi-particle systems.

The data obtained from photon and atomic experiments complement each other to provide a deeper understanding of how entanglement works in multi-particle systems. In experiments using photons, the data showed that entanglements could survive over very long distances, which shows great potential for quantum communication applications. However, in systems involving atoms, entanglement is more limited to shorter distances, which is relevant for applications in quantum computing.

The relationship between data from photon and atomic experiments provides new insights into the development of more efficient quantum systems. The merger of these two systems allows us to take advantage of the advantages of each particle in a wider range of applications. For example, the use of photons in quantum communication and atoms in quantum computing could be an ideal combination to address challenges in quantum technology.

By understanding the relationship between photons and atoms in multi-particle entanglement experiments, we can develop more integrated and efficient technologies. Therefore, further research to explore the combination of these two systems will be an important step in optimizing future quantum computing and communication applications.

The study showed that quantum entanglement can be maintained in multi-particle systems using photons and atoms, although there are significant differences in entanglement stability between the two. In experiments using photons, entanglements can survive at long distances of up to 1 kilometer, with a fairly high success rate (80%). On the other hand, experiments with atoms show that entanglement is limited to shorter distances (about 2 meters), with the level of entanglement decreasing faster as the distance between particles increases. These results indicate that photons are more resistant to external disturbances and more stable over longer distances than atoms.

The experiment also revealed that despite the increased distance between particles, photon systems can still maintain significant levels of entanglement, providing an idea that photon-based systems may be more suitable for quantum communication applications.

Meanwhile, atoms show potential for quantum computing applications even though they are limited to smaller distances. This data provides new insights into the stability and application of entanglement in various multi-particle systems.

Overall, the study confirms that although great challenges in maintaining entanglement in multi-particle systems remain, both types of particles—photons and atoms—demonstrate the ability to maintain entanglement under certain conditions, which opens up great opportunities for applications in quantum technology.

The results of this study are in line with previous research which showed that quantum entanglement can be maintained in two-particle systems, both photons and atoms. However, the research adds a new dimension by exploring multi-particle systems, which are more complex and more reflective of real-world applications, such as in quantum computing and quantum communication. Some previous research has tended to be limited to experiments with two connected particles, while this research expands our understanding of entanglement in larger systems.

The main difference between the results of this study and other studies is in terms of entanglement stability over longer distances. Other studies using photons have shown similar results, but this experiment confirms that even as the distance between particles increases, the level of entanglement remains high. In studies using atoms, previous data showed a decrease in entanglement over longer distances, but this study makes it clear that atoms have potential in quantum computing applications despite their limited distances.

What also sets this study apart is the measurement and testing of entanglement in two different systems under more extreme conditions, opening up space for further research that can explore the potential for entanglement in different types of particles and larger multi-particle systems.

The results of this study show that we are getting closer to the ability to develop more efficient quantum systems in real-world applications. This research signals that although the technical challenges in maintaining entanglement in multi-particle systems are still great, the potential to utilize entanglement in quantum communication and quantum computing is already very promising. Experiments showing that photons can be maintained over long distances signify that we have a stronger basis for developing a wider network of quantum communications.

This research also reflects the importance of the diversity of particle types used in quantum experiments. By understanding the advantages and limitations of photons and atoms, we can develop technologies that are more flexible and can be tailored to specific needs in a variety of applications, from communications to computing. These results are a sign that achievements in quantum entanglement will be the basis for more advanced future technologies.

In addition, the results of this study also lead to further questions about how entanglement can be maintained in larger and more complex systems. The success achieved in this experiment opens the door to further exploration that will provide a deeper understanding of how to manage entanglement in multi-particle systems involving more particles and more complex interactions.

The implications of the results of this study are enormous, especially in the field of communication and quantum computing. With the ability to maintain entanglement in larger multi-particle systems and over long distances, this research paves the way for the development of broader quantum communication networks. This technology allows information to be transmitted with a very high level of security, since the Heisenberg uncertainty principle can be applied to protect data transmitted through entanglement.

In addition, the results of this study also have important implications in the field of quantum computing. The discovery that atoms can be used in multi-particle systems for computing even though they are limited to shorter distances, provides an insight into how quantum computing systems can be further developed. The potential of atoms in more complex interactions opens up possibilities for more sophisticated quantum algorithms that can be applied to larger, more complex problems.

The implications of this research can also be felt in the field of quantum cryptography. With entanglement that can be maintained over longer distances, we can build a more secure cryptographic system, where data cannot be intercepted or altered by third parties without being detected. This will provide a solid foundation for protecting highly sensitive information in the future.

The results of this study are influenced by several factors related to the basic properties of the particles used in the experiment. Photons, which are light particles, have a longer coherence time and are more resistant to external disturbances, such as fluctuations in the magnetic field, which makes them more stable over longer distances. The success of this experiment shows that photons are superior in long-distance communication applications that require stable entanglement.

On the other hand, atoms are more sensitive to external environments, such as temperature and magnetic fields, which can lead to faster decoherence. However, atoms have an advantage in quantum computing applications due to their ability to interact in a more complex way compared to photons. The decrease in the degree of entanglement over longer distances suggests that atoms are more suitable for applications in smaller systems, such as in small-scale quantum computing.

Environmental conditions also play a big role in the results of this study. External disturbances, such as temperature changes or fluctuations in the magnetic field, can affect the stability of the entanglement in a multi-particle system (P. Yu dkk., 2019). Therefore, although photons and atoms show great potential, the main challenge is how to control and maintain the stability of the entanglement in more extreme and more complex conditions.

The next step is to continue research to develop more efficient methods of controlling and maintaining entanglement in larger multi-particle systems. Further research is needed to explore ways to reduce the influence of external disturbances on entanglement, both in photon and atomic systems. This will strengthen quantum communication applications that can be used to transmit information over a wider network.

In addition, further experiments need to be carried out to combine photons and atoms in larger and more complex systems, in order to explore the potential of entanglement in quantum computing applications. The development of this more integrated system will allow us to overcome the limitations of each particle and take advantage of their advantages in a wider range of applications.

Further research should also be focused on developing technologies that enable the measurement of entanglement in larger multi-particle systems. With more advanced tools, we can explore more deeply about how entanglement can be expanded and maintained under more complex conditions, opening up great possibilities for future applications of quantum technology.

CONCLUSION

The most important finding in this study is that quantum entanglement can be maintained in multi-particle systems, either by using photons or atoms, although there is a significant difference in entanglement stability between the two. Experiments involving photons show that entanglement can persist over very long distances (up to 1 kilometer), while atoms show a decrease in entanglement over longer distances, but still have potential for quantum computing applications on a smaller scale.

A major contribution to this research lies in the development of experiments that explore entanglement in larger multi-particle systems, as well as a deeper understanding of the differences between photons and atoms in maintaining entanglement. The experimental concepts and methods used in this study open up opportunities for further research on the application of entanglement in long-distance quantum communication and quantum computing, as well as provide a stronger foundation for the development of future quantum technologies.

The limitations of this study lie in the scale of the experiment which is still limited to relatively small and controlled systems, so it does not cover the full potential applications of larger multi-particle systems. Further research is needed to develop more effective techniques for maintaining entanglement on larger scales and under more extreme conditions, as well as to combine photons and atoms in more complex multi-particle systems for wider applications in quantum technology.

AUTHOR CONTRIBUTIONS

Look this example below:
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

REFERENCES

Almheiri, A., Engelhardt, N., Marolf, D., & Maxfield, H. (2019). The entropy of bulk quantum fields and the entanglement wedge of an evaporating black hole. *Journal of High Energy Physics*, *2019*(12), 63. https://doi.org/10.1007/JHEP12(2019)063

Bertini, B., Kos, P., & Prosen, T. (2019). Entanglement Spreading in a Minimal Model of Maximal Many-Body Quantum Chaos. *Physical Review X*, *9*(2), 021033. https://doi.org/10.1103/PhysRevX.9.021033

Bienfait, A., Satzinger, K. J., Zhong, Y. P., Chang, H.-S., Chou, M.-H., Conner, C. R., Dumur, É., Grebel, J., Peairs, G. A., Povey, R. G., & Cleland, A. N. (2019). Phonon-mediated quantum state transfer and remote qubit entanglement. *Science*, *364*(6438), 368–371. https://doi.org/10.1126/science.aaw8415

Bonen, S., Alakusu, U., Duan, Y., Gong, M. J., Dadash, M. S., Lucci, L., Daughton, D. R., Adam, G. C., Iordanescu, S., Pasteanu, M., Giangu, I., Jia, H., Gutierrez, L. E., Chen, W. T., Messaoudi, N., Harame, D., Muller, A., Mansour, R. R., Asbeck, P., & Voinigescu, S. P. (2018). Cryogenic Characterization of 22nm FDSOI CMOS Technology for Quantum Computing ICs. *IEEE Electron Device Letters*, 1–1. https://doi.org/10.1109/LED.2018.2880303

Cacciapuoti, A. S., Caleffi, M., Van Meter, R., & Hanzo, L. (2020). When Entanglement Meets Classical Communications: Quantum Teleportation for the Quantum Internet. *IEEE Transactions on Communications*, *68*(6), 3808–3833. https://doi.org/10.1109/TCOMM.2020.2978071

Chen, H. Z., Myers, R. C., Neuenfeld, D., Reyes, I. A., & Sandor, J. (2020). Quantum extremal islands made easy. Part I. Entanglement on the brane. *Journal of High Energy Physics*, *2020*(10), 166. https://doi.org/10.1007/JHEP10(2020)166

Corcoles, A. D., Kandala, A., Javadi-Abhari, A., McClure, D. T., Cross, A. W., Temme, K., Nation, P. D., Steffen, M., & Gambetta, J. M. (2020). Challenges and Opportunities of Near-Term Quantum Computing Systems. *Proceedings of the IEEE*, *108*(8), 1338–1352. https://doi.org/10.1109/JPROC.2019.2954005

Gong, M., Chen, M.-C., Zheng, Y., Wang, S., Zha, C., Deng, H., Yan, Z., Rong, H., Wu, Y., Li, S., Chen, F., Zhao, Y., Liang, F., Lin, J., Xu, Y., Guo, C., Sun, L., Castellano, A. D., Wang, H., … Pan, J.-W. (2019). Genuine 12-Qubit Entanglement on a Superconducting Quantum Processor. *Physical Review Letters*, *122*(11), 110501. https://doi.org/10.1103/PhysRevLett.122.110501

Graham, T. M., Song, Y., Scott, J., Poole, C., Phuttitarn, L., Jooya, K., Eichler, P., Jiang, X., Marra, A., Grinkemeyer, B., Kwon, M., Ebert, M., Cherek, J., Lichtman, M. T., Gillette, M., Gilbert, J., Bowman, D., Ballance, T., Campbell, C., … Saffman, M. (2022). Multi-qubit entanglement and algorithms on a neutral-atom quantum computer. *Nature*, *604*(7906), 457–462. https://doi.org/10.1038/s41586-022-04603-6

Ho, W. W., Choi, S., Pichler, H., & Lukin, M. D. (2019). Periodic Orbits, Entanglement, and Quantum Many-Body Scars in Constrained Models: Matrix Product State Approach. *Physical Review Letters*, *122*(4), 040603. https://doi.org/10.1103/PhysRevLett.122.040603

Hu, X.-M., Huang, C.-X., Sheng, Y.-B., Zhou, L., Liu, B.-H., Guo, Y., Zhang, C., Xing, W.-B., Huang, Y.-F., Li, C.-F., & Guo, G.-C. (2021). Long-Distance Entanglement Purification for Quantum Communication. *Physical Review Letters*, *126*(1), 010503. https://doi.org/10.1103/PhysRevLett.126.010503

Iadecola, T., & Schecter, M. (2020). Quantum many-body scar states with emergent kinetic constraints and finite-entanglement revivals. *Physical Review B*, *101*(2), 024306. https://doi.org/10.1103/PhysRevB.101.024306

Lago-Rivera, D., Grandi, S., Rakonjac, J. V., Seri, A., & De Riedmatten, H. (2021). Telecom-heralded entanglement between multimode solid-state quantum memories. *Nature*, *594*(7861), 37–40. https://doi.org/10.1038/s41586-021-03481-8

Larsen, M. V., Guo, X., Breum, C. R., Neergaard-Nielsen, J. S., & Andersen, U. L. (2021). Deterministic multi-mode gates on a scalable photonic quantum computing platform. *Nature Physics*, *17*(9), 1018–1023. https://doi.org/10.1038/s41567-021-01296-y

Lavasani, A., Alavirad, Y., & Barkeshli, M. (2021a). Measurement-induced topological entanglement transitions in symmetric random quantum circuits. *Nature Physics*, *17*(3), 342–347. https://doi.org/10.1038/s41567-020-01112-z

Lavasani, A., Alavirad, Y., & Barkeshli, M. (2021b). Measurement-induced topological entanglement transitions in symmetric random quantum circuits. *Nature Physics*, *17*(3), 342–347. https://doi.org/10.1038/s41567-020-01112-z

Levine, Y., Sharir, O., Cohen, N., & Shashua, A. (2019). Quantum Entanglement in Deep Learning Architectures. *Physical Review Letters*, *122*(6), 065301. https://doi.org/10.1103/PhysRevLett.122.065301

Li, Y., Chen, X., & Fisher, M. P. A. (2019). Measurement-driven entanglement transition in hybrid quantum circuits. *Physical Review B*, *100*(13), 134306. https://doi.org/10.1103/PhysRevB.100.134306

Liu, X., Hu, J., Li, Z.-F., Li, X., Li, P.-Y., Liang, P.-J., Zhou, Z.-Q., Li, C.-F., & Guo, G.-C. (2021). Heralded entanglement distribution between two absorptive quantum memories. *Nature*, *594*(7861), 41–45. https://doi.org/10.1038/s41586-021-03505-3

Marshman, R. J., Mazumdar, A., & Bose, S. (2020). Locality and entanglement in table-top testing of the quantum nature of linearized gravity. *Physical Review A*, *101*(5), 052110. https://doi.org/10.1103/PhysRevA.101.052110

Nahum, A., Roy, S., Skinner, B., & Ruhman, J. (2021). Measurement and Entanglement Phase Transitions in All-To-All Quantum Circuits, on Quantum Trees, and in Landau-Ginsburg Theory. *PRX Quantum*, *2*(1), 010352. https://doi.org/10.1103/PRXQuantum.2.010352

Pant, M., Krovi, H., Towsley, D., Tassiulas, L., Jiang, L., Basu, P., Englund, D., & Guha, S. (2019). Routing entanglement in the quantum internet. *Npj Quantum Information*, *5*(1), 25. https://doi.org/10.1038/s41534-019-0139-x

Stephenson, L. J., Nadlinger, D. P., Nichol, B. C., An, S., Drmota, P., Ballance, T. G., Thirumalai, K., Goodwin, J. F., Lucas, D. M., & Ballance, C. J. (2020). High-Rate, High-Fidelity Entanglement of Qubits Across an Elementary Quantum Network. *Physical Review Letters*, *124*(11), 110501. https://doi.org/10.1103/PhysRevLett.124.110501

Turkeshi, X., Biella, A., Fazio, R., Dalmonte, M., & Schiró, M. (2021). Measurement-induced entanglement transitions in the quantum Ising chain: From infinite to zero clicks. *Physical Review B*, *103*(22), 224210. https://doi.org/10.1103/PhysRevB.103.224210

Yin, J., Li, Y.-H., Liao, S.-K., Yang, M., Cao, Y., Zhang, L., Ren, J.-G., Cai, W.-Q., Liu, W.-Y., Li, S.-L., Shu, R., Huang, Y.-M., Deng, L., Li, L., Zhang, Q., Liu, N.-L., Chen, Y.-A., Lu, C.-Y., Wang, X.-B., … Pan, J.-W. (2020). Entanglement-based secure quantum cryptography over 1,120 kilometres. *Nature*, *582*(7813), 501–505. https://doi.org/10.1038/s41586-020-2401-y

Yu, P., Cheuk, L. W., Kozyryev, I., & Doyle, J. M. (2019). A scalable quantum computing platform using symmetric-top molecules. *New Journal of Physics*, *21*(9), 093049. https://doi.org/10.1088/1367-2630/ab428d

Yu, Y., Ma, F., Luo, X.-Y., Jing, B., Sun, P.-F., Fang, R.-Z., Yang, C.-W., Liu, H., Zheng, M.-Y., Xie, X.-P., Zhang, W.-J., You, L.-X., Wang, Z., Chen, T.-Y., Zhang, Q., Bao, X.-H., & Pan, J.-W. (2020). Entanglement of two quantum memories via fibres over dozens of kilometres. *Nature*, *578*(7794), 240–245. https://doi.org/10.1038/s41586-020-1976-7

Zhang, Z., Scully, M. O., & Agarwal, G. S. (2019). Quantum entanglement between two magnon modes via Kerr nonlinearity driven far from equilibrium. *Physical Review Research*, *1*(2), 023021. https://doi.org/10.1103/PhysRevResearch.1.023021

Zhong, Y., Chang, H.-S., Bienfait, A., Dumur, É., Chou, M.-H., Conner, C. R., Grebel, J., Povey, R. G., Yan, H., Schuster, D. I., & Cleland, A. N. (2021). Deterministic multi-qubit entanglement in a quantum network. *Nature*, *590*(7847), 571–575. https://doi.org/10.1038/s41586-021-03288-7