AkashaQ – Harnessing Quantum Decoherence

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1 Introduction

1.1 The Rise of Quantum Computing & Communication

Computing has been dominated by classical systems, where bits are represented as either a 0 or a 1, for an extremely long time. AI and machine learning leverage the foundations of classical computing to boost human teams' output, save time, and increase their effectiveness. Without requiring any development effort to figure out the technique, AI allows organizations to use a significant amount of traditional computational power to solve a poorly defined problem. However, because it is based on the ideas of classical computing, it still has limitations when it comes to solving specific kinds of issues, according to Chris Balance, co-founder and CEO of Oxford Ionics.[1]

However, quantum systems have the potential to change computing entirely. They process information using qubits that are in numerous states at the same time. Quantum supremacy, which allows quantum computers to do tasks that are impossible for classical systems, is made possible by using entanglement and superposition.

Entanglement describes how two subatomic particles can be closely related to one another, causing them to function as a single, cohesive entity regardless of their distance from one another, making it extremely fundamental to both quantum technology and quantum mechanics[2], while the capacity of a quantum system to behave as though it is in several states simultaneously until it is measured is known as superposition.[3]

According to these principles, quantum systems may very efficiently handle complicated problems with a large number of interacting variables. For example, quantum computers are capable of efficiently handling cryptography and optimization problems that defy traditional machines.[4]

Nevertheless, quantum computing systems do come with a fair share of challenges as well, ranging from software-hardware difficulties to qubit decoherence, with qubit decoherence serving as arguably the biggest one.[5]

Since the quantum state of qubits is so delicate and may be affected unpredictably by any disturbance, such a minor vibration or a change in temperature, any stored information can be destroyed, making quantum computers far more vulnerable to noise than classical computers. Decoherence is a massive problem in quantum computing since computations must be finished before decoherence to prevent errors, and thus far, there is no substantive solution to this issue.[6]

Additionally, there’s also Quantum Error Correction and Scalability. A key component of quantum computing is quantum error correction (QEC), however, the structure of qubits and the quantum no-cloning theorem make it difficult. Fault-tolerant quantum processing is still very difficult to achieve, despite advancements. Surface code

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[1] Baker, Berenice. “Quantum vs. Classical AI Computing: Expert Reactions.” *Iotworldtoday.com*, 2024, www.iotworldtoday.com/quantum/quantum-vs-classical-ai-computing-expert-reactions. Accessed 10 Feb. 2025.

[2] Ravi, Vajiram. “Quantum Entanglement - Meaning, Theory, Applications.” *Vajiram & Ravi*, 16 May 2024, vajiramandravi.com/quest-upsc-notes/quantum-entanglement/. Accessed 10 Feb. 2025.

[3] Wright, Gavin. “Superposition - Definition from WhatIs.com.” *WhatIs.com*, Dec. 2024, www.techtarget.com/whatis/definition/superposition. Accessed 11 Feb. 2025.

[4] Thomas, Jack. “The Future of Computing: How Quantum Information Is Revolutionising Technology.” *Innovation News Network*, 7 Jan. 2025, www.innovationnewsnetwork.com/the-future-of-computing-how-quantum-information-is-revolutionising-technology/54261/. Accessed 11 Feb. 2025.

[5] Swayne, Matt. “What Are the Remaining Challenges of Quantum Computing?” *The Quantum Insider*, 24 Mar. 2023, thequantuminsider.com/2023/03/24/quantum-computing-challenges/. Accessed 11 Feb. 2025.

[6] Canorea, Elena. “Quantum Computing: Potential and Challenges Ahead.” *Plain Concepts*, 19 June 2024, www.plainconcepts.com/quantum-computing-potential-challenges/. Accessed 11 Feb. 2025.

and other topological quantum error correcting codes have become popular because of their easy implementation and high error threshold. Another issue is scalability, as mistakes are more likely to occur as a quantum computer's qubit count rises. The goal of software firms like IBM's Quantum System One is to preserve qubit quality as the system grows. Investigating novel qubit varieties may result in quantum computers that are easier to scale and more error resistant. Anyons are theoretical particles that only exist in two dimensions, and Microsoft's Quantum Lab is conducting research to be able to harness them to create a topological quantum computer.[7]

1.2 The Importance of Qubit Coherence

As mentioned in the previous section, qubit decoherence is arguably the biggest challenge hindering the success of quantum computing. While this one singular line is enough to display the sheer necessity of qubit coherence, this section will dive deep into the concept.

Let's first begin by defining qubit coherence for clarity in the sections to follow. The capacity of a quantum system to preserve a distinct phase connection between several states in a superposition is known as coherence. The parallelism and interference that are essential to quantum computing are made possible by this fundamental characteristic, which permits qubits to exist in a linear combination of base states. Quantum activities need coherence, which is delicate and readily lost by interactions with the surroundings. In quantum algorithms, coherence permits both constructive and destructive interference by maintaining the relative phase between these states. Quantum calculations become useless when the qubit loses its quantum behavior due to a lack of coherence.[8]

Multiple environmental factors can affect the coherence of a quantum system. For instance, heat can decohere a qubit since it provides the system with thermal energy. Decoherence is also introduced into the system by undesired electric and magnetic forces. These fields pair with the surroundings and have the ability to drive quantum states. Crosstalk, which occurs when qubits contribute errors to one another, is another cause of this phenomenon.[9]

The ability to sustain coherence for longer periods of time is the most important factor for the development of larger, more powerful quantum computers. Longer coherence times would allow deeper quantum circuits, allowing more sophisticated calculations before decoherence stops computation. This would see a transition from small-scale proof-of-principle quantum processors to fully scalable quantum systems with the potential to surpass classical supercomputers in problems such as molecular simulation, optimization, and AI acceleration.

1.3 Quantum Error Correction's Role in Qubit Coherence

In the context of decoherence, which results from undesired interactions between the quantum system and its surroundings, Quantum Error Correction (QEC) codes are essential for preserving the integrity of quantum information. QEC, like the surface code, which compresses a logical qubit into many physical qubits to identify and fix faults brought on by decoherence, is one method of reducing decoherence (Gottesman, 1996). The surface code works very well against two frequent faults that arise in quantum systems because of decoherence: bit-flip and phase-flip errors. The Shor code, which converts a logical qubit into nine physical qubits, is another QEC algorithm that has drawn a lot of interest (Shor, 1995). Several quantum platforms have been used to

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[7] Tarraf, Giorgio. "The Quantum Conundrum: Challenges to Getting Quantum Computing on Deck." *Atelier.net*, 21 Sept. 2023, atelier.net/insights/quantum-conundrum-challenges-quantum-computing. Accessed 11 Feb. 2025.
[8] "What Is Coherence." *Www.quera.com*, www.quera.com/glossary/coherence. Accessed 12 Feb. 2025.
[9] "Coherence." *Qutube.nl*, 2019, www.qutube.nl/solutions/fundamentals-27/coherence-232. Accessed 12 Feb. 2025.

experimentally show the Shor code's ability to fix any single-qubit mistake. However, the demand for low error rates and precise control over numerous qubits makes practical implementation of QEC codes extremely difficult.

For instance, quantum information may be encoded using topological codes, which are naturally resistant to decoherence (Kitaev, 2003). Non-Abelian anyons, exotic quasiparticles that result from the collective behavior of many qubits, are used in these algorithms. Topological codes may be superior to conventional QEC codes and have been demonstrated to be very effective against specific kinds of mistakes. Another method for QEC is concatenated codes, which combine many QEC codes in a hierarchical fashion (Knill, 2005). This makes it feasible to fix more complicated mistakes than could be done with only one code. Concatenated codes may be superior to conventional QEC codes and have been demonstrated to be very effective against specific forms of decoherence. [10]

However, while quantum error correction is one of the most reliable methods to fight against decoherence, it does come with a fair few challenges as well. These include, but are not limited to –

Current hardware sources fail to maintain Quantum Fidelity – the measure of the accuracy of the performance or preparation of a quantum state or operation – and Coherence Time – defined previously; thus, QEC codes fail to work as required.

Most computers in today's day and age do not have the sufficient computing power to handle the many physical qubits required by QEC codes such as the Shor code.

Currently, the error threshold – the highest permitted error rate necessary for the code to operate efficiently – for QEC codes is rather high.

Fault Tolerance – the technique that guarantees the application of mistake repair without creating new errors – has still not been achieved, however, it is an active topic of research.

These challenges call for novel methods to combat Qubit Decoherence.[11] This paper will be discussing one of those theoretical methods: the theorized ability of quantum vacuum to contain fluctuating fields that carry quantum information. Instead of merely counteracting decoherence, could we exploit the very mechanisms that cause it?

2 Theoretical Foundation

2.1 Understanding the Quantum Vacuum

Before I begin discussing its theorized ability to contain fluctuating fields that carry quantum information, we must know what the quantum vacuum really is and what those fluctuating fields may be caused by.

The traditional view of reality has been called into question by quantum physics, which has revealed that the vacuum is actually a realm teeming with quantum activity. In addition to being essential for theoretical physics,

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[10] "Breaking down Quantum Decoherence: Challenges and Solutions." *Quantum Zeitgeist*, 9 Sept. 2024, quantumzeitgeist.com/breaking-down-quantum-decoherence-challenges-and-solutions/#theoretical-models-of-decoherence. Accessed 14 Feb. 2025.

[11] Saripalli, Janakiram. "Quantum Error Correction: A Review of Methods, Challenges, and Advances." *International Journal of AdvancedResearch in Science, Engineering and Technology*, vol. 11, no. 11, 2024, www.ijarset.com/upload/2024/november/01-janakiram-05.pdf. Accessed 14 Feb. 2025.

this reinterpreted concept of the vacuum has important applications in particle physics, cosmology, and new technology. In the past, the void was thought of as being a place of nothingness, a blank canvas devoid of matter and energy, or simply "nothing." But this intuitive idea has undergone through a significant transformation since the development of quantum mechanics.

The vacuum was viewed in classical physics as a blank canvas, an immobile and inert stage on which physical events that could be measured and thought about developed. However, when quantum physics advanced in the early 20th century, this notion started to shift. Researchers like Max Planck, Niels Bohr, and numerous others started to realize that the atomic and subatomic world did not obey the laws of classical physics and, in certain situations, went against the Euclidean and mechanistic conception of reality. They discovered that the so-called "vacuum" is actually a breeding ground for physical phenomena that defy our comprehension of reality, including quantum fluctuations, virtual photons, antiparticles, and energies.

Going off on a tangent, here's a fact which is rather fascinating about the quantum vacuum: The baseline energy of the quantum vacuum is called zero-point energy. Even the "emptiest" location is bustling with activity, as this idea demonstrates. The ramifications are profound: this energy may help to explain the dark energy that is responsible for the universe's accelerating expansion. However, there is a 120-order-of-magnitude difference between theoretical predictions and empirical evidence, which is one of physics' biggest unsolved mysteries.[12]

Returning to the central discussion – before we begin to fully understand how the quantum vacuum may be harnessed to transfer information, we must first understand quantum fluctuations.

The correlation of electrons in atoms and molecules, the zero-point energy of harmonic oscillators, the effects of tunnelling, the spontaneous formation of matter-antimatter particle pairs, and other phenomena in quantum mechanics are all referred to as "quantum fluctuations." All of these events are characterized by the presence of a "superposition state." Particles and fields can simultaneously exist in two or more states according to quantum physics. The remaining state is sometimes described as a "quantum fluctuation" when one of the states predominates.

For instance, a superposition of the states 99% "heads" and 1% "tails," where the tiny 1% contribution of the tails state may be interpreted as a quantum fluctuation, might be created if we assume a quantum mechanical coin that can exist in the single states "heads" and "tails." There are two types of "quantum fluctuations": dynamic and static. A "quantum fluctuation" that is dynamic (or time-dependent) is the development of a superposition state over time. The existence of the wavefunction in a superposition state at a certain moment in time is referred to as a static (or time-independent) "quantum fluctuation."[13]

Now that we have an understanding of the quantum vacuum and quantum fluctuations, let's discuss the evidence for the hypothesis.

2.2 Evidence for the Information-bearing Capabilities of Quantum Fluctuations

Quantum fluctuations convey information by the wave function ψ, which describes the state of a quantum system and its probabilistic inherent characteristics. The measurement outcomes predicted by theory correspond to the probabilities calculated from the wave function, which is the probability of obtaining specific results in

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[12] Meroli, Stefano. "The Quantum Vacuum: The Most Dynamic Essence of the Universe." *Www.scienceshot.com*, 26 July 2023, www.scienceshot.com/post/the-mysteries-of-the-quantum-vacuum-the-most-dynamic-essence-of-the-universe. Accessed 15 Feb. 2025.

[13] Shenvi, Neil. "Do Quantum Fluctuations Show That Something Can Come from Nothing?" *Neil Shenvi - Apologetics*, 8 Mar. 2018, shenviapologetics.com/do-quantum-fluctuations-show-that-something-can-come-from-nothing/. Accessed 15 Feb. 2025.

experimental measurements. This demonstrates that information in quantum states is encoded in the statistical record of measurement outcomes, specifically in entangled and interacting systems and measuring apparatus.

However, the interpretation is with restrictions. The inherent uncertainty of quantum measurement brings philosophical issues with the wave-function collapse phenomenon, in the sense that not all outcomes can be known with absolute certainty. Also, the imposition of specific conditions of measurement and the nature of observables might restrict the general applicability of the results since different experimental setups can give different interpretations of the same quantum state, thus rendering the understanding of how information is encoded in quantum systems in all cases more complex.[14]

With constant advancements in scientific understanding, quantum fluctuations have grown to have measurable effects as well, such as the Casimir effect and the Lamb shift.

2.2.1 The Casimir Effect

Let's begin by discussing the Casimir effect; the Casimir effect is caused by quantum fluctuations that create a difference in pressure between the plates. The fluctuating electromagnetic fields in the vacuum exert forces that push the mirrors closer together, thus showing that even 'empty' space is teeming with quantum activity. It is often called the Casimir force. Given that the mirrors are within microns of one another, the Casimir force may be measured and is sensitive to changes in distance. When the impact was initially anticipated in 1948, it was challenging to quantify using the tools available at the time. However, the Casimir effect is now easy to analyze because of advanced technology.

The following equation illustrates how the Casimir force is proportional to the mirrors' cross-sectional area and grows 16 times for every halving of the distance between them:

$$F \sim \frac{A}{d^4}$$

where F is the force, A is the cross-sectional area of the mirrors and d is the distance between them, with other factors being Planck's constant and the speed of light.

The Casimir effect provides a striking example of how quantum fluctuations are not just theoretical constructs but have real measurable effects. If these fluctuations can exert forces, could they also be harnessed to store or transmit information?[15]

However, before we begin exploring the main hypothesis, let's explore the Lamb shift.

2.2.2 The Lamb Shift

The Lamb-Retherford experiment's findings are enough to demonstrate that quantum fluctuations do have very tangible impacts. One way to think of it is that the atom itself is always there and that it exerts the Coulomb

[14] Konishi, Kenichi. "Quantum Fluctuations, Particles and Entanglement: A Discussion towards the Solution of the Quantum Measurement Problems." *International Journal of Modern Physics A*, vol. 37, no. 17, World Scientific, June 2022, https://doi.org/10.1142/s0217751x22501135. Accessed 16 Feb. 2025.

[15] Lambrecht, Astrid. "The Casimir Effect: A Force from Nothing – Physics World." *Physics World*, Sept. 2002, physicsworld.com/a/the-casimir-effect-a-force-from-nothing/. Accessed 16 Feb. 2025.

force, an electromagnetic force that controls electrostatic attraction. The average Coulomb force differs significantly from what it would be in the absence of the quantum fluctuations in the electromagnetic field because the electron's location varies due to these fluctuations. These quantum fluctuations, which manifest as virtual photons from the charged particles in the atom, have a distinct effect on the 2S and 2P orbitals due to their slightly different geometries. This physical phenomenon is now known as the Lamb shift.

Although the shift of a free electron will undoubtedly differ from that of a bound electron, even free electrons will eventually interact with the quantum vacuum. The quantum nature of the universe is unavoidable wherever you go. With a measurement of the fine structure constant, α, to better than 1-part-in-1,000,000, the hydrogen atom is now one of the most demanding test subjects for the laws of quantum physics. The universe is quantum, and this applies to both particles and fields. For over 75 years, our tests have shown that this inevitable fact is more than just theory.[16]

Having established two of the main evidence for quantum fluctuations' measurable effects, let's turn our attention now to the main hypothesis.

2.3 The Hypothesis

Aside from their quantum mechanical intrinsic operation, vacuum fluctuations can potentially act as a dynamic quantum information carrier. If controlled perturbations of the vacuum initiate the creation of observable quantum state phase shifts, it would indicate the potential for information encoding and information extraction by modulating vacuum properties. It could, in principle, provide an ultra-high security and noise-immunity channel for information transmission, with applications in quantum communication and in cryptographic protocols.

The hypothesis states that quantum fluctuations, phenomena that have already displayed measurable effects such as the Lamb shift and Casimir effect, have the potential to be harnessed to store and transmit information in a novel way. In this paper so far, we've discussed how quantum fluctuations can carry probabilistic data through the wave function and go as far as influencing physical interactions at a microscopic scale. This leads us to propose that quantum fluctuations can very well be systematically manipulated. I aim to leverage their role in quantum entanglement, virtual particle interactions, and perturbations in the quantum field to develop a framework where quantum fluctuations can be used as a medium for encoding, preserving, and transmitting information; this may lead to a complete paradigm shift in current transmission techniques and quantum computing.

In fact, the hypothesis mimics the Hindu cosmological entity, Akasha. Hindu cosmology defines the fifth element, Akasha, as an all-pervading, information-bearing medium, and this definition is strikingly similar to our subject matter – hence making this project inherently rooted in Hindu culture. If information is the basis of existence, can vacuum fluctuations be a quantum data storage device, much like the Akashic Records of ancient wisdom?

3 Experimental Setup

The Mach-Zehnder Interferometer (MZI) setup in the AkashaQ project is intended to detect and investigate the influence of quantum vacuum fluctuations on the phase of light. The interferometer consists of two beam

[16] Siegel, Ethan. "The Reality of Quantum Fluctuations Was Proven Back in 1947." *Big Think*, 25 July 2024, bigthink.com/starts-with-a-bang/reality-quantum-fluctuations-1947/. Accessed 17 Feb. 2025.

splitters (BS1 and BS2), two mirrors (M1 and M2), and two detectors (D1 and D2). A coherent source of light such as a laser is divided into two paths at BS1, so the beams travel distinct optical paths before they are brought back together at BS2. Constructive and destructive interference would generally control the intensity distribution at D1 and D2 in standard conditions. If quantum fluctuations affect the phase of light in one of the paths, it could potentially be able to cause measurable distortions in the interference pattern. To check for this, we add a controllable quantum vacuum perturbation field—a well-controlled setup where vacuum fluctuations could be controlled by external conditions such as electromagnetic field fluctuations or Casimir-like boundary conditions. Any phase shifts resulting from this would demonstrate that quantum fluctuations can encode and manipulate information in a controlled manner, demonstrating that the hypothesis that the quantum vacuum can be utilized as an information-bearing medium could be correct.

To run a computational representation of this experiment, I'm going to use QuTiP, which, using Python, is an excellent framework for simulating quantum optical systems. The evolution of the quantum state in the interferometer will receive a lucid description using density matrices and wavefunctions, allowing me to study coherence effects. I will set up Hamiltonians for the light-matter interactions, allowing for the vacuum fluctuation terms that are externally controlled. By simulating the expected phase shifts under different conditions, I predict interference patterns that would emerge if quantum fluctuations have a tangible impact. The analyses that I can perform with these simulations will help me to build a better experimental expectation that provides the greatest sensitivity in detecting small changes in phases caused by vacuum effects. This computational approach assures that my theoretical predictions are compatible with the experimental data and reinforces our foundation to study the quantum vacuum as a functional resource in information processing.

4 Conclusion

Quantum computing provides a shift in paradigm with potential to outpace classical computers on challenging problems. However, problems such as qubit decoherence, quantum error correction boundaries, and scalability limit its application. This paper explores an alternative perspective, leveraging the quantum vacuum and its fluctuating fields to carry quantum information. Evidence, such as the Casimir Effect and the Lamb Shift, help support the belief that quantum fluctuations can be used to store and carry information, if the right conditions are present, with the potential of producing more stable quantum systems. Additional research, such as the AkashaQ project, is needed to assess the practicality of this hypothesis. By reframing decoherence as a potential opportunity, we have the potential to unlock new potential in quantum computation and communication.

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