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Review Article

Quantum Computation and Universe

Suresh Kumar S*

Department of Aeronautical Engineering, Alagappa University, Karaikudi, India

ABSTRACT

It is argued in this paper that universal Quantum Error Correction (QEC) codes for cosmological computations are implemented for fault tolerant functionality with minimal error probabilities. Unlike discrete-variable systems, Continuous Variable (CV) systems possess an infinite dimensional Hilbert space. Encoding the quantum information in CV systems, therefore, provides a hardware efficient approach to QEC.

Various bosonic codes have been experimentally demonstrated to suppress errors in CV systems. These can be extended to quantum vacuum superfluid condensate and hadronic quark gluon plasma liquid systems in nature in which we may implement QEC non-adaptively *via* engineered dissipation an approach called Autonomous QEC (AutoQEC). We can introduce an explicit AutoQEC scheme for the squeezed cat, SC, against loss errors by engineering a non-trivial dissipation. Electroweak fields and gravity fields would account for correcting errors and removing the entropy such that quantum information is not fragile to environment noise in cosmological computations at quantum and relativistic orders in nature.

Keywords: Quantum Error Correction (QEC); Fault Tolerant Quantum Computation (FTQC); Bosonic; Electrodynamics

INTRODUCTION

Quantum information is fragile to errors introduced by the environment. Quantum Error Correction (QEC) protects quantum systems by correcting the errors and removing the entropy [1]. Based upon QEC, Fault Tolerant Quantum Computation (FTQC) can be performed, provided that the physical noise strength is below an accuracy threshold [2]. However, realizing FTQC is yet challenging due to the demanding threshold requirement and the significant resource overhead [3]. Unlike Discrete Variable (DV) systems, Continuous Variable (CV) systems possess an infinite dimensional Hilbert space. Encoding the quantum information in CV systems, therefore, provides a hardware efficient approach to QEC. Various bosonic codes have been experimentally demonstrated to suppress errors in CV systems [4]. It is repirted that we may implement QEC non-adaptively *via* engineered dissipation an approach called Autonomous QEC (AutoQEC) [5].

LITERATURE REVIEW

AutoQEC against excitation loss, which is usually the dominant error source in a bosonic mode, remains challenging. It requires either large nonlinearities that are challenging to engineer (e.g. the multiphoton processes needed for n-fold rotation symmetrical codes with $n \geq 4$ [6] or couplings to an intrinsically nonlinear DV system that is much noisier than the bosonic mode [7].

The scheme is based on the Squeezed Cat (SC) encoding which involves the superposition of squeezed coherent state [8]. We can introduce an explicit AutoQEC scheme for the SC against loss errors by engineering a non-trivial dissipation, which simultaneously stabilizes the SC states and corrects the loss errors.

The proposed dissipation can be implemented with the same order of nonlinearity as that required by the two component cat, which has been experimentally demonstrated in superconducting circuits [9]. It is shown to be feasible in trapped-ion systems [10].

Correspondence to: Suresh Kumar S, Department of Aeronautical Engineering, Alagappa University, Karaikudi, Indias; E-mail: ssk54in@yahoo.co.in

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We can show that the stabilized SC qubits also possess a biased noise channel (with one type of error dominant over others), with an even larger bias (defined to be the ratio between the dominant error rate and the others) nearly equal to e to the power n squared (compared to for the cat), where n denotes the mean excitation number of the codewords. Consequently, we can concatenate the stabilized SC qubits with a DV code tailored towards the biased noise to realize low-overhead fault tolerant QEC and quantum computation [11]. We can develop a set of operations for the SC that are compatible with the engineered dissipation and can preserve the noise bias needed for the concatenation.

Hence we can achieve one-to-two orders of magnitude improvement in the k1/k2 threshold, where k1 is the excitation loss rate and k2 is the engineered dissipation rate, for the surface-SC and repetition-SC scheme (compared to surface cat and repetition cat, respectively).

Furthermore, the repetition SC can achieve a logical error rate as low as 10 to power -15, which already suffices for many useful quantum algorithms, even using a small SC with under a practical noise ratio k1/k2=1/2=10 to power -3 m [12].

We can note that aspects of the SC encoding were also recently studied in ref. 8, with an emphasis on the enhanced protection against dephasing provided by squeezing. However, ref. 8 neither explored the enhanced noise bias provided by squeezing, nor exploited the ability to concatenate the SC code with outer DV codes using bias preserving operations; as discussed, these are key advantages of the SC approach, as in ibid ref 17, providing an explicit, fully autonomous approach to SC QEC that exploits low order nonlinearities.

Typical bosonic systems suffer from excitation loss, heating and dephasing errors, with loss being the prominent one. We can explain why the SC code can correct the loss errors by analyzing the Knill-Laflamme error correction conditions, and evaluating the QEC matrices [13].

While it can be shown that the SC encoding can, in principle, detect and correct the loss errors, it remains a non-trivial task to find an explicit and practical recovery channel, so that we can perform photon counting measurement on a probe field that is weakly coupled to the gauge mode. And a feedback parity flip is applied on the logical qubit upon detecting an excitation in the probe field [14]. Such measurement and feedback process can be equivalently implemented by applying the dissipative dynamics.

DISCUSSION

As per cited literature we can propose two reservoir engineering approaches to implement such a non-trivial dissipator, which utilizes three bosonic modes that are nonlinearly coupled. As shown in literature a high quality mode b and a lossy mode c, together, serve as a nonreciprocal bath that provides a directional interaction from the gauge mode to the logical qubit in the storage mode a. Such a coupled system can be physically realized in, e.g. superconducting circuits.

SC can be autonomously protected from excitation loss, heating and dephasing. We may note that the SC encoding also emerges as the optimal or close-to-optimal single mode bosonic code through a bi-convex optimization procedure for a loss and dephasing channel with dephasing being dominant [15].

We can apply the autonomously protected SC for computational tasks, for which we need to have a set of gate operations, such that are they are compatible with the engineered dissipation, as also preserve the biased noise channel of the SC. This implies a system which can be utilized for resource efficient concatenated QEC and fault tolerant quantum computing [16].

The surface cat scheme can arbitrarily suppress the errors in a resource efficient manner once the ratio between the loss rate k1 and the engineered dissipation rate k2 is below a certain threshold.

For studied cases in the 1/2 thresholds (e.g. ~5 × 10 t power -4 for the surface cat) are very low because of the low-fidelity bias preserving operations [17]. Also, the minimal logical error probability of the repetition cat (e.g. ~10 t power -2 for n equal 4) is not low enough for fault tolerant algorithms, except for cats with very large mean photon number, because of the limited noise bias.

It has also been shown that these challenges can be overcome by using the dissipative SC. That means that the k1/k2 thresholds for both the surface code and the repetition code can be significantly improved by concatenating with the dissipative SC. Moreover, the repetition-SC can reach sufficiently low logical error probability ~10^{-15} even with a small SC n equal 4.

For a practical noise ratio k1/k2=10^{-3}, the minimal logical error probability of the repetition-SC can reach ~10 t^{-15}, which suffices for many useful quantum computational tasks.

The ground state of a pair of ultrastrongly coupled bosonic modes is predicted to be a two mode squeezed vacuum. However, the corresponding quantum correlations are currently unobservable in condensed matter where such a coupling can be reached, since it cannot be extracted from these systems. Here, we can show that superconducting circuits can be used to perform an analog simulation of a system of two bosonic modes in regimes ranging from strong to ultrastrong coupling [18]. There is emerging interest in utilizing bosonic modes for quantum information processing, with circuit Quantum Electrodynamics (circuit QED) as one of the leading architectures. Quantum information can be encoded into subspaces of a bosonic superconducting cavity mode with long coherence time [19].

CONCLUSION

We can extend such notions to hadronic QCD systems with color superconductivity in quark gluon plasma fluids as equivalents of superfluid high energy fields. In the light of the above discussions they would represent an AutoQEC, providing possibilities in nature for quantum computations of a fault tolerant nature. In such natural systems based on quantum vacuum superfluids condensates and quark gluon plasma fluids, at the low and high end energy spectrum, considerably lower error probabilities can be theoretically attained, in the light of the above discussions based on physical superconducting systems at experimental scales in engineered studies, as depucted in the foregoing descriptions, based on literature. This can be extended to natural quantum vacuum and hadronic systems as representing low energy and high energy quantum computing in a highly fault tolerant manner based on AutoQEC superconductor like systems with ultralow error probabilities. We can even argue that electroweak fields and gravity fields would represent naturally engineered dissipation losses.

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