Quantum Simulating Neutrino Oscillations

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Background

Quantum computers use quantum physics (e.g. quantum states) to store data and perform computations [3]. With an arbitrary number of energy levels, qudits, for example, can be manipulated via microwave pulses such that the differences in their frequencies and energies provide information about a system [2]. The use of pulses to output information makes up the theory of quantum simulations.

The neutrino oscillation phenomenon (the oscillation of the small neutrino between its three types) is measured through quantum mechanical probabilities, making it an ideal candidate for simulating on quantum computers.

$$= \begin{bmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{bmatrix}\begin{bmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta_{CP}}\\0&1&0\\-\sin\theta_{13}e^{i\delta_{CP}}&0&\cos\theta_{13}\end{bmatrix}\begin{bmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{bmatrix}$$

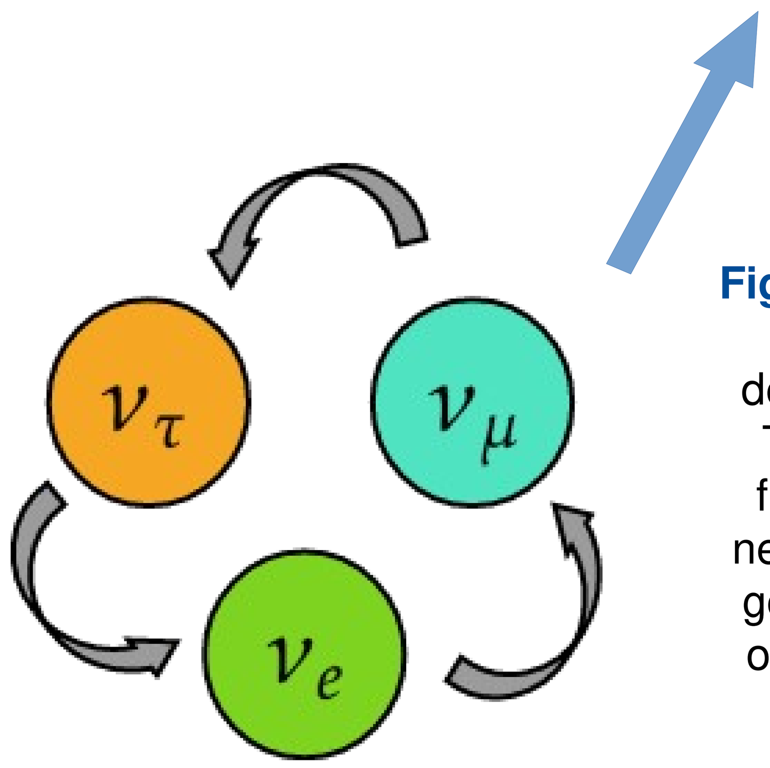

Figure 1: The oscillation between neutrino types (left), which is mathematically described by the PMNS* matrix (top) [1]. This matrix accounts for the mass and flavor states of the neutrinos as well as neutrino mixing angles and phases [1]. In general, it generates probabilities, which oscillate due to the sine and cosine with their respective mixing angles.

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References

[1] M.C. Gonzalez-Garcia and M. Yokoyama. "Neutrino Masses, Mixing, and Oscillations," (2019).

[2] B. Özgüler and D. Venturelli, "Numerical gate synthesis for quantum heuristics on bosonic quantum processors," (2022).

[3] C. A. Argüelles and B. J. P. Jones, "Neutrino oscillations in a quantum processor," (2019).

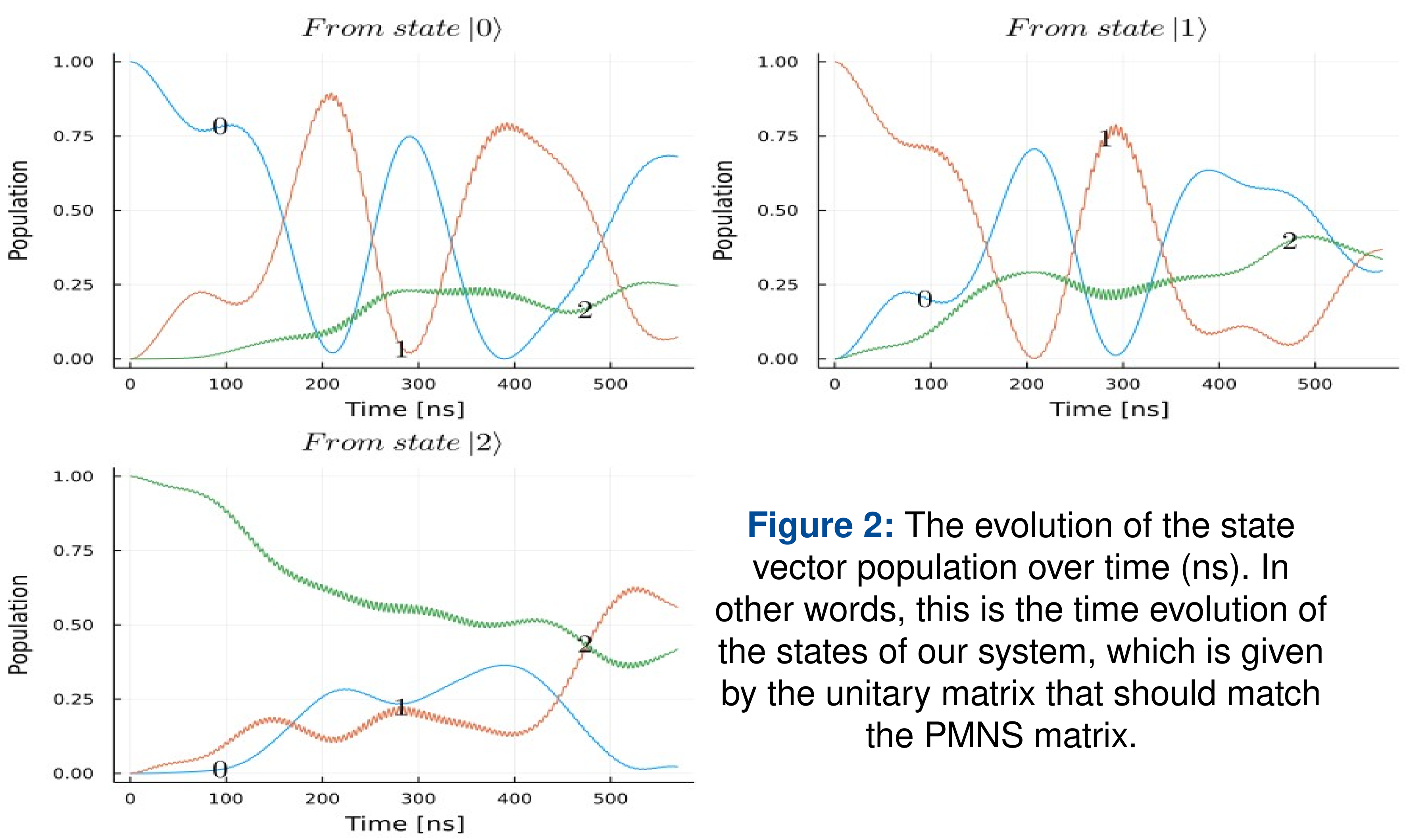

Figure 2: The evolution of the state vector population over time (ns). In other words, this is the time evolution of the states of our system, which is given by the unitary matrix that should match the PMNS matrix.

Purpose

Quantum computers can simulate three-flavor neutrino oscillations with less computational power than classical computers [3].

One can test our oscillation models from quantum computers against those from classical computers. This comparison provides insight into whether theoretical simulations match experimental data, and how simulations can be improved to match what is expected.

Methods

Juqbox (designed for small, closed quantum systems like neutrino oscillations) is used to generate microwave pulses that act on our three energy-level qudit (a qutrit) [2]. Each energy level is mapped to a state of the target unitary PMNS matrix.

Initial pulse characteristics are given: pulse duration and seed number, for example. Additionally, we include the simulation parameters like max number of iterations and the system's Hamiltonian, which drives the time evolution of the energy of our simulation.

Given these parameters as input, Juqbox's optimization functions can output the closest unitary matrix to the PMNS.

Results

The results demonstrated that the fidelity reached a maximum fidelity of **99.9998715%** with a pulse duration of 570 ns and 1000 max iterations.

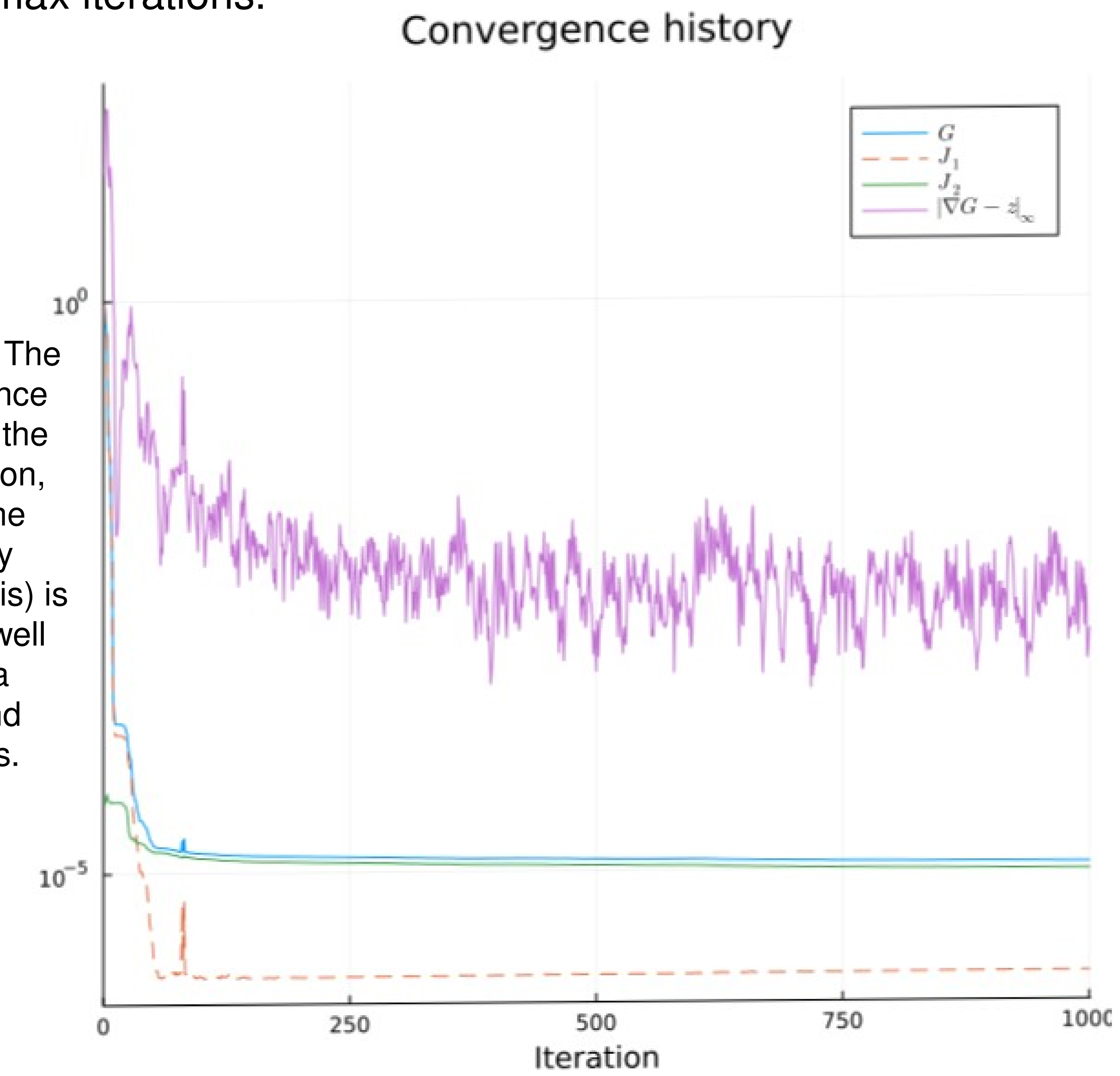

Figure 3: The convergence history of the optimization, where the infidelity (vertical axis) is reached well within a thousand iterations.

Conclusion

Given the high fidelity and (Fig. 2), the quantum simulator seems to match the expected mass/flavor unitary transformations.

Future work can be done in running the system on another independent classical simulator tool (QuTiP) to check the validity of the result. The result could then be sent to an actual quantum computer. Intrinsic errors present in quantum computers would need to be mitigated thereafter.

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