Simulating Gravitationally-Induced Entanglement Between Two Massive Particles Using Superconducting Qubits

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The extremely small value of the gravitational coupling constant and the absence of evidence of the existence of a graviton that encompasses the quantum aspect of gravity make the current quantum gravity theories almost impossible to be practically tested. In this paper, we build on the quantum information principle that if two quantum systems can entangle through a mediating system, then the latter system must also be quantum. Proposing two masses each in positional superposition -as the two quantum systems- interacting solely via their mutual gravitational field -as the mediating system- utilizing IBM's 156-qubit superconducting quantum processor `ibm_fez`, and without imposing any quantum control over gravity, we were able to observe quantum-like features associated with the classical gravitational field. The entanglement signature between the two masses in our analysis is attributed to the gravitational field quantization.

I. INTRODUCTION

Understanding the quantum nature of gravity constitutes one of the major concerns facing modern physics. Despite the verification of the general relativity (classical theory) at vast scales, the behavior of gravity in the realm of quantum world is still an open question. According to a vital suggestion for testing this connection, the gravitational field itself supposed to produce "quantum entanglement" [1, 2]. Referring to the theory of quantum information, any medium that causes entanglement between two objects is considered to a be quantum entity. Consequently, if two massive bodies are in a superposition and entangled through their gravitational contact, it would demonstrate that the gravitational field acts as a quantum field, whereas the classical field cannot accomplish such a feat.

Following by the theoretical proposals, a series of experiments designed to investigate the quantum properties of gravity in a lab setting have been inspired by the idea of utilizing gravity to create entanglement. This approach avoids the requirement for the previously believed enormous energies [1, 2]. Creating and verifying entanglement between massive objects is the key challenge in this endeavor, a difficult task considering their great susceptibility to decoherence and external noise.

Superconducting quantum circuits/qubits, have emerged as a potent modeling technique to get around several experimental obstacles. In this work, we use a quantum simulation based on a superconducting processor to investigate the quantum aspect of gravity. We use the protocol given by Marletto and Vedral [2] to describe a configuration in which two objects each pass through a Mach-Zehnder interferometer. The simulation we use converts this bodily structure into a quantum circuit, i.e, every object's route superposition is stored in a superconducting qubit, where the beam splitters are carried out using quantum gates. By measuring the final state of the qubit pair, we can determine if this simulated gravity interaction produces the entanglement signal that indicates a quantum nature.

The rest of this paper is organized as follows. In Sec. II, we give a concise overview about the effects of quantum gravity. In Sec. III, the experimental geometry and setup is illustrated, while in Sec. IV we show the simulation and the results of our experiment. Finally, we conclude the main findings of our work in Sec. V.

II. QUANTUM ASPECTS OF GRAVITY

Quantum effects of gravity are extremely hard to detect due to the weak coupling of the gravitational force. Detecting gravitons, which will provide evidence of the quantum/particle nature of gravity seems practically impossible. However, progress in quantum experiments such as in atom interferometry has helped in observing gravitational effects precisely. Here, we discuss one such proposal involving gravitational interaction between two superposed particles. For an ideal experimental setup and the calculations presented below, we assume negligible non-gravitational interactions. The effects due to other forces will be discussed later. The experiment involves two equal masses with only interaction being gravitation. For slowly moving, well-localized masses, the dominant interaction is the Newtonian potential energy. The interaction Hamiltonian can be written as

$$H_{int} = V(r_1, r_2) \approx -\frac{Gm^2}{|r_1 - r_2|} = \frac{Gm^2}{d_{ab}}, \tag{1}$$

where G is Newton's gravitational constant and d_{ab} is the inter-mass distance. If the mass spends time Δt in the specific path with a distance d_{ab}, the quantum time-evolution operator for the above potential is

$$U = exp(-\frac{i}{\hbar}\int_0^{\Delta t} H_{\rm int} dt). \tag{2}$$

This gives a phase factor

$$e^{i\phi_{ab}} = e^{-iV_{ab}\Delta t/\hbar} \tag{3}$$

$$\phi_{ab} = -\frac{V_{ab}\Delta t}{\hbar} = \frac{Gm^2}{\hbar d_{ab}}\Delta t \tag{4}$$

Newtonian gravity is a valid approximation for these scales and there is no need for GR corrections. This also assumes that there is no significant momentum transfer, and the potential only imprints a phase. Now, we consider a two-mass quantum state used in Ref. [2] and try to get the closed form of the entanglement as a function of the gravitational phases. This is detailed in the Appendix, and the post interaction state can be given by

$$|\psi\rangle = \frac{1}{2}(|00\rangle + e^{i\phi_1}|01\rangle + e^{i\phi_1}|10\rangle + e^{i(\phi_1+\Delta\phi)}|11\rangle), \tag{5}$$

We use this result for modelling the gravitational interaction as a Unitary matrix and evolve the states. There are many factors that can affect the phase measurement and the entanglement test. A few important details to consider are the precision of the distance measurement d_{ab}, because even tiny changes in distance results in random fluctuations of ϕ which washes out entanglement. The interaction time Δt must be stable as the fluctuations again give phase noise. The masses should also remain in coherent superposition so that the gravitational potential acts like a branch-dependent phase shifter. Some of the external factors to consider in table-top experiments of quantum gravity are discussed in Ref. [3] and are as follows.

A. Factors to consider

Environmental decoherence: External factors such as gas, photons or other vibrations can influence the off diagonal terms of the density matrix and kills the gravitational phase information and therefore the entanglement. Collision of each gas acts like a measurement of which path, which results in loss of coherence (Ref. [4]). To avoid this influence of phase shift, the experiments should be done in ultra-high vacuum (UHV)/cryogenic UHV.

Emitted or absorbed radiation (Ref. [5]) has information of the path and the decoherence rate of thermal emission scales as the sixth power of temperature. This can cause random phase kicks and that is the reason cryogenic operations are proposed. This can also help in avoiding internal vibrational modes.

Diósi–Penrose gravitational decoherence: It is a 'proposed' modification (Refs. [6, 7]) in which a superposition of mass distributions has an instability as they result in different curvature of spacetime. As nature can't support two spacetime geometries, and the timescale of the spontaneous collapse of superposition is given by

$$\tau_{DP} \sim \frac{\hbar}{\Delta E_G}, \tag{6}$$

where ΔE_G is the gravitational self-energy of mass-density difference between the two configurations superimposed. If this decoherence collapse timescale is much smaller than the Δt, then this process will destroy the off-diagonal terms and so the gravitational phase factors and so the entanglement.

Other fluctuating potential differences could mimic the gravitational phase. Casimir energy also can contribution its own phase and could lead to phase noise. In fact, any coupling that produces an interaction energy between the branches can contribute to the phase and should be taken carefully.

Relativistic corrections: The gravitational phase calculation is derived from the Newtonian potential as shown above. This is the leading order term in the post-Newtonian approximation/expansion of General Relativity. The higher order corrections are in fact of the order of $O\left(\frac{v^2}{c^2}\right)$ and $O\left(\frac{GM}{c^2 d}\right)$. Considering the case of the proposed experiments, velocities of the trapped masses are much less than c, and so the corrections are very small and irrelevant for entanglement generation (Refs. [1, 2]). Similarly, other higher order effects such as decoherence from emission of gravitons are extremely irrelevant for our problem.

III. EXPERIMENTAL SETUP

In this paper, we designed and executed a digital quantum simulation of Marletto and Vedral's proposed quantum-information-theoretic approach [2] to testing whether the gravitational field is quantized. The experiment is as follows: each mass travels through a Mach-Zehnder Interferometer, as shown in Fig. 1. They first interact with separate beam splitters ($BS1_1, BS1_2$), which put each mass in equal superpositions of their two possible paths through their respective interferometers. After each mass passes through their BS1, and before they reach their second beam splitters ($BS2_1$, $BS2_2$), they acquire a relative phase due to the gravitational potential energy experienced while being separated by distances d_1 and d_2 from each other. This relative phase is defined as:

$$\Delta\phi = \phi_2 - \phi_1, \tag{7}$$

where ϕ_1 and ϕ_2 refer to the gravitational phases accumulated as the two masses propagate at fixed distances d_1 and d_2 from each other. Once each mass reaches BS2, its relative phase determines which detector it travels to. The probabilities p_0, p_1 for each mass to arrive at their interferometers' Detector 0 (D0) and Detector 1 (D1), respectively, are:

$$p_0 = \frac{1}{2}\left(\cos^2\frac{\phi_1}{2} + \cos^2\frac{\Delta\phi}{2}\right), \tag{8}$$

$$p_1 = \frac{1}{2}\left(\sin^2\frac{\phi_1}{2} + \sin^2\frac{\Delta\phi}{2}\right). \tag{9}$$

Using IBM's superconducting quantum processing unit (QPU) `ibm_fez`, we modeled the gravitational interaction as a two-qubit controlled-phase Unitary:

$$U_{\text{grav}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\phi_1} & 0 & 0 \\ 0 & 0 & e^{i\phi_1} & 0 \\ 0 & 0 & 0 & e^{i(\phi_1+\Delta\phi)} \end{pmatrix} \tag{10}$$

acting on two qubits which represent the separate masses. We test 15 separate relative phase values with a fixed ϕ_1 to analyze how the gravitationally-induced phase difference affects (i) the single-mass detector probabilities p_0 and p_1, and (ii) the bipartite entanglement of the resulting two-qubit state, quantified by the negativity $N(\rho)$.

We use the diluted maximum-likelihood algorithm for quantum tomography [8] to reconstruct the approximate two qubit density matrix representing the output state of the two-qubit system for a range of relative phase values. We analyze three quantities of interest:

1. Expectation Values for Joint Pauli Bases (Fig. 2),
2. Single-Mass Detector Probabilities p_0, p_1 as a function of relative phase $\Delta\phi$ between qubits (Fig. 3),
3. Strength of Entanglement as a function of $\Delta\phi$, determined by the observed Negativity (Fig. 4).

For each of the 9 possible joint Pauli bases, the expectation values are calculated as:

$$\langle\sigma_A \otimes \sigma_B\rangle = \mathrm{Tr}[(\sigma_A \otimes \sigma_B)\rho]. \tag{11}$$

Given the ideal target state $|\psi_5\rangle$ (see appendix A), the state fidelity is then computed as:

$$F = \langle\psi_5|\,\rho\,|\psi_5\rangle \tag{12}$$

To measure the degree of entanglement between the positional degrees of freedom of the two masses in our experiment, we use the resulting density matrix to calculate the Negativity of the joint two-qubit system. For a bipartite state ρ with subsystems A and B, the negativity is defined as [9]:

$$\mathcal{N}(\rho) = \frac{\left\|\rho^{T_B}\right\|_1 - 1}{2}, \tag{13}$$

where ρ^{T_B} refers to the partial transpose of ρ with respect to subsystem B [9]. Equivalently,

$$\mathcal{N}(\rho) = -\sum_i \lambda_i, \text{ with } \lambda_i \leq 0. \tag{14}$$

Thus, we use only the negative eigenvalues of ρ^{T_B} to calculate the strength of entanglement present in each density matrix. For a maximally-entangled pure two-qubit state, i.e. the Bell state, the negativity is maximized:

$$N_{\max} = \frac{1}{2}. \tag{15}$$

This maximal entanglement occurs when $\phi_1 = 2\pi n$ and $\Delta\phi = \pi$, where n is an integer [2].

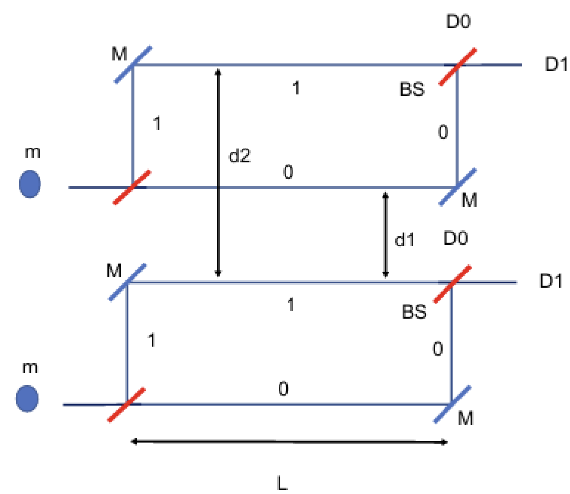

FIG. 1. Interferometry Setup as shown in Ref. [2]. Two masses pass through sets of beam splitters, and acquire a gravitational phase as they propagate at distances d_1, d_2 from each other. Detectors D0, D1 are triggered based on the relative phase.

IV. SIMULATION OF SETUP

Our experiment was run on IBM's 156-qubit QPU `ibm_fez` device via Qiskit Runtime. We chose physical qubits 4 and 5 due to their reported low noise levels and high coherence times (see Appendix C). The gravitational interaction was modeled as a custom two-qubit unitary matrix (Eq. (10)), and Hadamard gates were used to model the beam splitters.

We chose a fixed $\phi_1 = 0$, and defined 15 equally-spaced relative phases $\Delta\phi \in [0, 2\pi]$. For each relative phase value, a set of 9 tomography circuits (one for each possible joint Pauli basis) was constructed. Since the `ibm_fez` QPU only supports measurements in the Pauli Z basis, we applied rotational gates to measure in the Pauli X/Y bases. All 9 circuits were transpiled with `optimization_level = 3` and executed with 2048 shots each, contributing 276,480 system measurements.

We then used the reconstructed density matrix to calculate the joint Pauli expectation values via Eq. (11), the single-mass detector probabilities p_0, p_1 via

$$p_0 = \mathrm{Tr}[(|0\rangle\langle 0| \otimes \mathbb{I})\,\rho] = \langle 00|\,\rho\,|00\rangle + \langle 01|\,\rho\,|01\rangle\,, \quad (16)$$

$$p_1 = \mathrm{Tr}[(|1\rangle\langle 1| \otimes \mathbb{I})\,\rho] = \langle 10|\,\rho\,|10\rangle + \langle 11|\,\rho\,|11\rangle\,, \quad (17)$$

and the entanglement strength $\mathcal{N}(\rho)$ via Eq. (14).

For our chosen reference phases $\phi_1 = 0$ and $\Delta\phi = 1$ radian, we achieve a target state fidelity $F \approx 0.978$, which indicates that our reconstructed state highly resembles the ideal gravitationally-induced entangled state. Furthermore, as seen in Fig. 2, our observed joint Pauli expectation values align closely with the theoretical values calculated from eq. 11 for the reference values $\phi_1 = 0$, $\Delta\phi = 1$. The largest difference of 0.04 occurred for $\langle ZZ\rangle$.

From Figs. 3 and 4, it can be seen that for phase differences $\approx 2\pi n$, the entanglement strength goes to zero and the detector probabilities shift toward deterministic behavior: for $\Delta\phi = 0$, p_0 reaches its maximum value of ≈ 0.9977, while $p_1 \approx 0.0022$. For $\Delta\phi \approx \pi$, $p_0 \approx 0.5052$, while $p_1 \approx 0.4947$. This maximal convergence in detector probabilities coincided with the highest value of observed negativity. Thus, the higher the degree of entanglement was, the more probabilistic the detector outcomes became. Also, the maximum negativity value observed was ≈ 0.456. It occurred at phase difference $\approx \pi$ from our tested $\phi_1 = 0$, in agreement with Eq. (15).

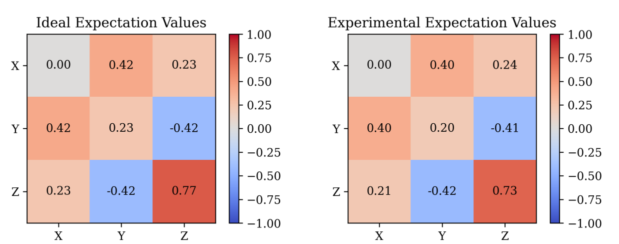

FIG. 2. Heatmaps of Joint Pauli Expectation Values for Reference Phase Values $\phi_1 = 0$, $\Delta\phi = 1.0$ radian.

V. RESULT AND CONCLUSION

In our work using the IBM quantum computer we simulated the gravitationally induced entanglement between the two particles, we used the method introduced in Ref. [2], which used the interference pattern developed between the two ends of Mach-Zehnder Interferometer. Compare to other method of testing quantum gravity (eg: detecting a graviton in LHC), interferometry is most promising as the effects of quantum gravity are subtle and due to other interactions very hard to detect but interference pattern may be able to capture these effect as we have seen in detection of gravitational waves. Under the reasonable assumptions (as discussed in previous sections) our simulation results are in well agreement with that of theoretical calculations: as shown in the heatmap

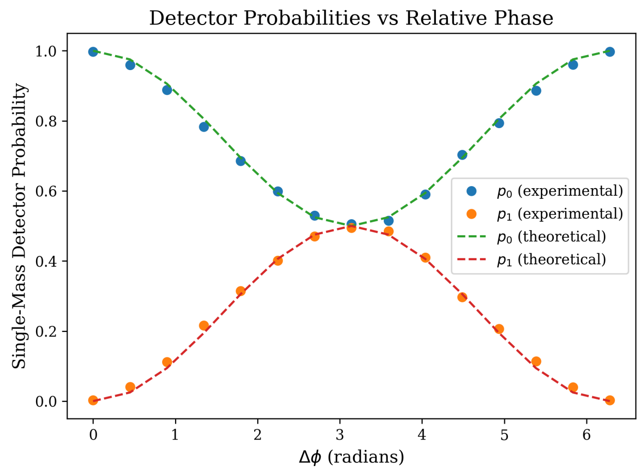

FIG. 3. Single-Mass Detector Probabilities as a function of Relative Phase. Dotted lines show theoretical predictions, blue and orange dots show experimental calculations across 15 relative phase values.

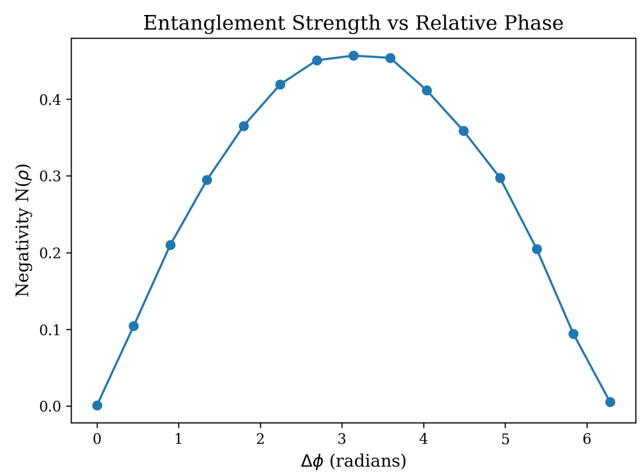

FIG. 4. Negativity Calculations for 15 different reconstructed density matrices with separate relative phase values. Negativity peaks near $\Delta\phi = \pi$.

Fig 2. Another quantity of our interest is detector probability as function of the phase difference, which is shown in Fig 3, whereas the entanglement strength is shown Fig 4. Since our calculation was done on IBM quantum computer which are susceptible to noise we had quantum noise present in our simulation although small, still our simulation are in good starting point for performing future calculations by adding effects related to experimental setup.

Data Availability

All experimental data and code written for this project are publicly available at GitHub.

[1] S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. A. Geraci, P. F. Barker, M. Kim, and G. Milburn, Spin entanglement witness for quantum gravity, Physical review letters **119**, 240401 (2017).

[2] C. Marletto and V. Vedral, Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity, Phys. Rev. Lett. **119**, 240402 (2017).

[3] D. Carney, P. C. E. Stamp, and J. M. Taylor, Tabletop experiments for quantum gravity: a user's manual, Classical and Quantum Gravity **36**, 034001 (2019).

[4] K. Hornberger, S. Uttenthaler, B. Brezger, L. Hackermüller, M. Arndt, and A. Zeilinger, Collisional decoherence observed in matter wave interferometry, Phys. Rev. Lett. **90**, 160401 (2003).

[5] O. Romero-Isart, A. C. Pflanzer, F. Blaser, R. Kaltenbaek, N. Kiesel, M. Aspelmeyer, and J. I. Cirac, Large quantum superpositions and interference of massive nanometer-sized objects, Phys. Rev. Lett. **107**, 020405 (2011).

[6] L. Diósi, Models for universal reduction of macroscopic quantum fluctuations, Phys. Rev. A **40**, 1165 (1989).

[7] R. Penrose, On Gravity's role in Quantum State Reduction, General Relativity and Gravitation **28**, 581 (1996).

[8] J. Řeháček, Z. Hradil, E. Knill, and A. I. Lvovsky, enDiluted maximum-likelihood algorithm for quantum tomography, Physical Review A **75**, 042108 (2007).

[9] G. Vidal and R. F. Werner, Computable measure of entanglement, Physical Review A **65**, 032314 (2002).

Appendix A: Time-Evolution of 2-Qubit State

BS1 and BS2 are modeled by single Hadamard gates on the respective qubit. For qubit 1, both BS1 and BS2 are modeled as $H \otimes I$, and for qubit 2, both BS1 and BS2 are modeled as $I \otimes H$.

Since each qubit is initialized to $|0\rangle$ on `ibm_fez`, the time evolution of our two-qubit system begins with the state:

$$|\psi_0\rangle = |00\rangle\,. \tag{A1}$$

After interacting with BS1, qubit 1 is left in an equal superposition of simultaneously being in the lower arm of the interferometer and being in the upper arm, while qubit 2 is still definitively in the lower arm:

$$|\psi_1\rangle = \mathrm{BS1}_1\,|00\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |10\rangle\right). \tag{A2}$$

Once both qubits have interacted with their beam splitters, the two qubits are both in equal superpositions of their two possible paths through their interferometers:

$$|\psi_2\rangle = \mathrm{BS1}_2\,|\psi_1\rangle = \frac{1}{2}\left(|00\rangle + |01\rangle + |10\rangle + |11\rangle\right). \tag{A3}$$

The application of our U_{grav} unitary matrix imparts the simulated gravitational phases acquired by each of the masses to the qubits in our experiment:

$$|\psi_3\rangle = U_{grav}\,|\psi_2\rangle$$

$$= \frac{1}{2}\left(|00\rangle + e^{i\phi_1}\,|01\rangle + e^{i\phi_1}\,|10\rangle + e^{i(\phi_1+\Delta\phi)}\,|11\rangle\right), \tag{A4}$$

$$|\psi_4\rangle = \mathrm{BS2}_1\,|\psi_3\rangle\,. \tag{A5}$$

After both masses interact with their second beam splitters (i.e. the second Hadamard is applied to each qubit), the system is in the final state which we use to calculate detector probabilities and reconstruct the joint density matrix for analyses:

$$|\psi_5\rangle = \mathrm{BS2}_2(\mathrm{BS2}_1\,|\psi_3\rangle) = \frac{1}{4}\Big[\left(1 + 2e^{i\phi_1} + e^{i(\phi_1+\Delta\phi)}\right)|00\rangle$$

$$+\ \left(1 - e^{i(\phi_1+\Delta\phi)}\right)|01\rangle +\ \left(1 - e^{i(\phi_1+\Delta\phi)}\right)|10\rangle$$

$$+\ \left(1 - 2e^{i\phi_1} + e^{i(\phi_1+\Delta\phi)}\right)|11\rangle\Big]. \tag{A6}$$

Appendix B: Detector Probabilities

From our $|\psi_5\rangle$, the explicit forms of p_0 and p_1 can be obtained:

$$p_0 = \mathrm{P(D0)} = |\langle 00|\,\psi_5\rangle|^2 + |\langle 01|\,\psi_5\rangle|^2 =$$

$$\left|\left(\frac{1}{4} + \frac{1}{2}e^{i\phi_1} + \frac{1}{4}e^{i(\phi_1+\Delta\phi)}\right)|00\rangle + \left(\frac{1}{4} - \frac{1}{4}e^{i(\phi_1+\Delta\phi)}\right)|01\rangle\right|^2 \tag{B1}$$

$$p_1 = \mathrm{P(D1)} = |\langle 10|\,\psi_5\rangle|^2 + |\langle 11|\,\psi_5\rangle|^2 =$$

$$\left|\left(\frac{1}{4} - \frac{1}{4}e^{i(\phi_1+\Delta\phi)}\right)|10\rangle + \left(\frac{1}{4} - \frac{1}{2}e^{i\phi_1} + \frac{1}{4}e^{i(\phi_1+\Delta\phi)}\right)|11\rangle\right|^2 \tag{B2}$$

Appendix C: Noise Parameters

We analyzed IBM's official calibration data for `ibm_fez` and chose to use physical qubits 4 and 5 based on their low readout assignment errors (0.003295898 and 0.006225586, respectively) and high T_1, T_2 coherence times (qubit 4: T_1 = 178.8150991 us, T_2 = 102.7111401 us; qubit 5: T_1 = 146.7707984 us, T_2 = 137.9348414 us) on the day we performed the experiment (November 27th 2025). Readout assignment error gives the probability of an inaccurate measurement; if qubit 4 is in state $|0\rangle$ but is measured as $|1\rangle$, that constitutes a readout error. T_1 is the relaxation time; this is the time it takes a qubit in its excited state $|1\rangle$ to relax back to its ground state $|0\rangle$. Having a higher value is advantageous so that we can preserve qubit values of 1 long enough to run our circuit. T_2 gives the phase coherence time, which quantifies how long the phase information for a superposition state can be maintained without environmental decoherence.