JOINT INSTITUTE FOR NUCLEAR RESEARCH

Laboratory Of Information Technologies

FINAL REPORT ON THE INTEREST PROGRAM

Introduction To Quantum Computing

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Contents

1 Abstract

The project we were presented aimed to introduce us to the physics ground of quantum computing, and how are these principles are applied in our real life world. Throughout the whole project, we studied the theory of the ideas, and applied them in different experiments as shall be shown in the upcoming sections of the report. We started from the definition of a two-level system and quibits which are considered the fundamental building block of the signals transmitted, to the quantum gates and how they revolutionized computer theories, including experiencing Quiskit experiments measurement.

2 Introduction - Spin Quantum Mechanics

After the revolutionary advancement that has been encountered in quantum mechanics after Heisenberg and Schrodinger, the year 1922 showed that a lot has yet to be discovered, after the results that have been shown in the famous Stern-Gerlach experiment, revealing the spin property of the electron. In brief, hot silver atoms have been bombed through an in-homogeneous magnetic field, where classically due to the neutrality of the atoms no deviation should be recorded on the screen, yet the astonishing division of the beam into two suggested another coupling that is occurring with the magnetic field other than the dipole moment of the bombarded atoms. It turned out that a two-level system, termed as spin -either up or down-, classified to be a quantum intrinsic angular momentum property of the electrons interacted with the magnetic field.[1] Further information about spin mechanics can be found in introductory quantum mechanics books.

Accompanying implications are shown as follows:

1. All two-level system dynamics are analogous to the spin mechanics.

2. Qubit model is considered to be a two-level system as shall be shown.

3. Entanglement phenomenon is observed within the different measurements of the two level systems, including the qubit model.

[1]A two-level system in sense that two states are super-positioned upon each other

3 Methodology

3.1 Qubits

The transferred signal in classical computational architecture is a bit, and analogously the transferred signal in quantum computing is the *qubit*, which is a superposition of two states: $|0\rangle$ and $|1\rangle$, i.e. a two-level system. Superconducting platforms shall be used to generate such quantum bits. This can be achieved by exciting the atoms of a superconductor to excited energy levels, then by using a non-linear inductor, namely **Josephson's Junction** we can isolate the energy levels, or in other words we *discretize* the levels to the namely $|0\rangle$ and $|1\rangle$. Josephson's Junction is basicaly built up from two superconductors coupled by thin insulating barrier, through which the current tunnels. In order to perceive a persistent source for the qubits, the **Transmon Qubit** is embedded in our circuit as shown in Fig.

3.2 Qubit Measurements

The following experiments are conducted on the superconducting platform explained above, and shall help us identify some of the characteristics of qubits. 2 complex (CPP) packages, namely CPX and SU(2), have been implemented with **HYBERLit Supercomputer** to work out the exercises.

3.2.1 Resonance Frequency Scan

The resonance frequency is defined to be the energy difference between the ground and the excited states $|0\rangle$ and $|1\rangle$. A system has been designed where the energy gap between the two states were large enough to be able to measure it accurately. ROOT has been used to fit the graph with the obtained measurements from **IBM Quiskit** platform.

3.2.2 Rabi Experiment

This experiment aims to calibrate a π pulse corresponding to the frequency obtained, in order to determine the transition between these two states specifically. Starting by small amplitude pulses,we incrementally increase the amplitudes of the given signals, keeping track of when the qubit flips. This is the resonance frequency calculated, fitted in a sine curve as shall be shown.

3.2.3 0/1 Discrimination

From quantum mechanics postulates, the wave function of the given system collapses to a single value, i.e corresponding to one of the eigenvalues and eigenstates of the system, after applying a certain measurement on it. After applying a π pulse, one needs to be able to know what state the qubit collapsed to, which is the aim of this experiment. A cluster of states can be obtained and plotted by applying progressive pi pulses over an ensemble of qubits, or repeating the same experiment over and over again. Elaboration on such discrimination can be found in the results section.

3.2.4 Relaxation Time T1

A system after being excited to an excited state, tends to lose its energy in some certain form to be able to transfer for a more stable state, namely the ground state. Our excited qubits takes a certain time for such a process to occur, defined as the relaxation time T1. A time tracker is applied exactly after π pulse is applied, and measures the delay time taken by the qubit to return to the ground state. Measurements where tracked by **IBM Qusikit** platform.

These experiments are enough to represent the most basic measurements that could be done on the qubit system and identify its characteristics. More modifications can happen on the way we design the experiment to obtain better results, for instance:

3.2.5 Ramsey Experiment - Modification for generating a pulse

In the preceding sections, we generated the pi pulse one shot. As for the Ramsey experiment, we obtain a similar pulse by first generating $\frac{\pi}{2}$, waiting for a time interval δt, and finally obtaining a similar $\frac{\pi}{2}$ pulse. Frequency differences between then two methods was also measured and discussed at the results section.

3.2.6 T2 Determination and Hahn Echoes

Similar to the concept of relaxation time, we define T2 as the coherence time of the qubit as a measurement of how long it could survive. Measurement of T2 is done as follows:

A Ramsey experiment is conducted followed by sending a π pulse at a given time τ. This helps in the cancellation/reversal of the accumulation of phases; yet, it results in an echo at time 2τ where the second $\frac{\pi}{2}$ pulse is sent. This resulted echo is also known as *Hahn Echo*.

3.2.7 Dynamical Decoupling

Aims to cancel out the frequencies of noise, to lengthen the system's coherent times. This can be achieved by applying consecutive π pulses instead of a single pulse.

4 Results

As for the explained methodologies, we now plot the obtained results.

4.1 Frequency Scan

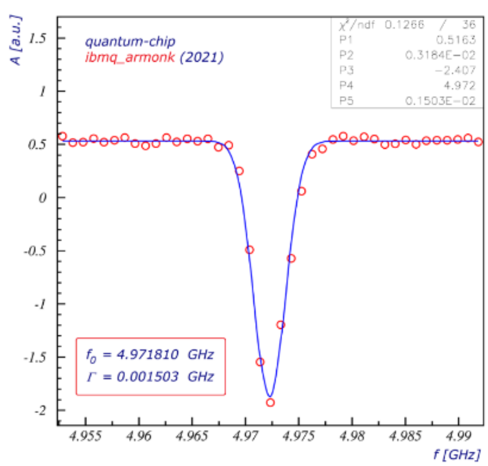

Figure 1: Pulse amplitude of the qubit.

The blue line is the fit performed ROOT while the red dots represent the experimental data. The fit function is found to be:

$$\frac{A}{\pi}\frac{B}{\left(x-q_{freq}\right)^2+B^2}+C \tag{1}$$

The resonant frequency value is found to be: $f_0 = 4.971$ GHz.

4.2 Rabi Experiment

The fit curve is:

$$A\cos\frac{2\pi x}{d}-\phi+B \tag{2}$$

where d is the driving period, and A corresponds to the probability density of finding the system in the final state $|1\rangle$.

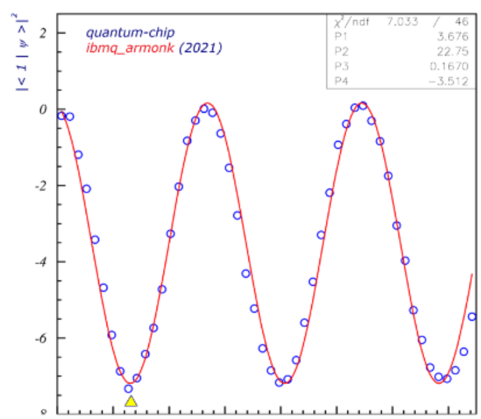

Figure 2: π pulse fitted by ROOT.

4.3 0/1 Discriminator

Here, the same experiment was carried several times rather than performing the measurement over an ensemble of qubits as our system. The borderline shows the discrimination between the ground and the excited states:

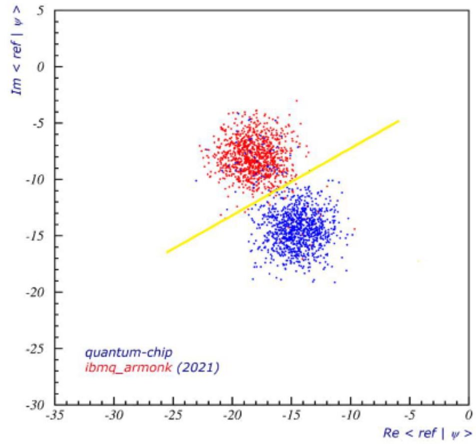

Figure 3: The yellow line discriminates between the two states.

4.4 T1 Relaxation time

The fit function obtained by ROOT is:

$$A \exp^{-\frac{x}{T_1}} + C \tag{3}$$

and the relaxation time $T_1 = 6.734 \mu s$

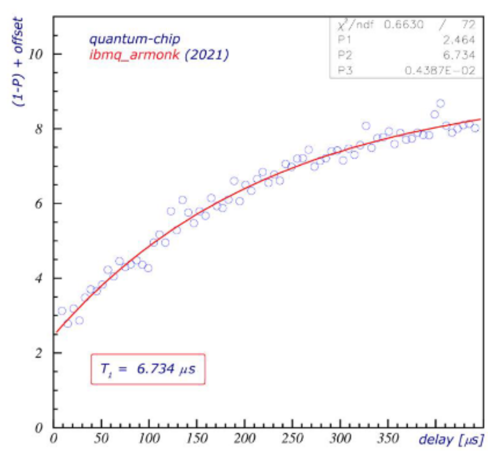

Figure 4: Delay time versus (1-P) with an offset for the relaxation time.

4.5 Ramsey Experiment

The fit function is:

$$A \cos 2\pi d_f x - C + B \tag{4}$$

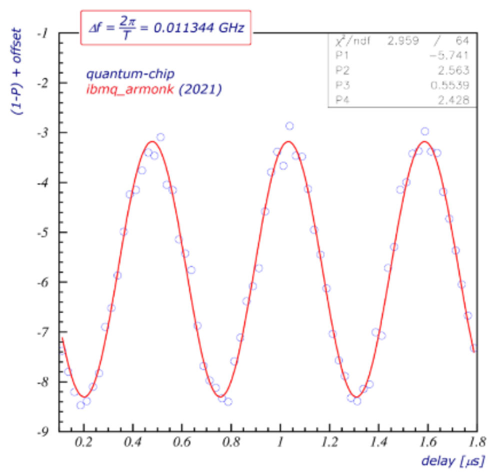

Figure 5: Delay time versus (1-P) with an offset for the difference in frequencies.

4.6 Hanh Echo and T2

Similar fit curve function to the relaxation time is found for the coherence time, expressed as follows:

$$A \exp^{-\frac{x}{T_2}} + C \tag{5}$$

and the coherence time value is $T2 = 286.4 \mu s$

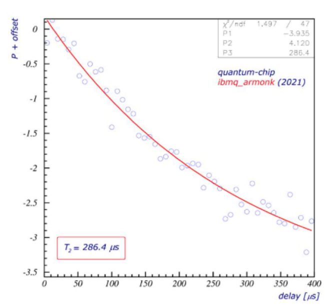

Figure 6: Delay time vs (P) with an offset for the coherence time T2

4.7 Dynamical Decoupling

After applying Ramsey experiment, the fit curve is modified to be:

$$A \exp^{-\frac{x}{T_{2DD}}} + C \tag{6}$$

and the coherence time $T_{2DD} = 317.7\mu s$

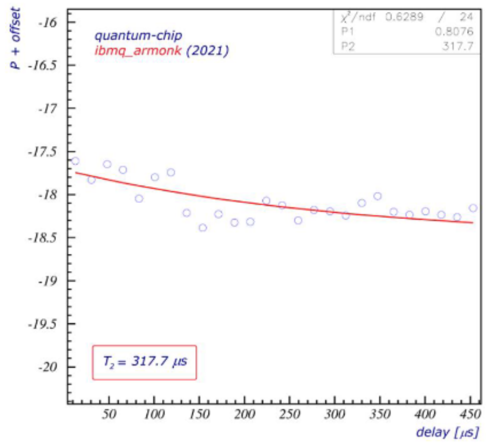

Figure 7: Delay time vs (P) with an offset for the coherence time.

5 Quantum Grover Algorithm

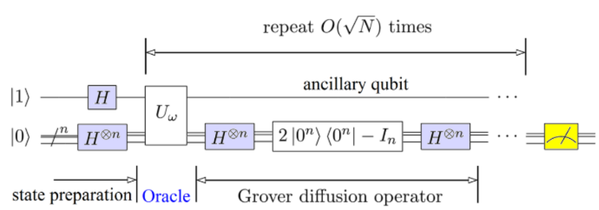

Figure 8: Quantum Grover Algorithm Diagram

6 Conclusion

In this wave, we investigated the basic fundamentals of quantum computing physics, what characterizes them, tracking and measuring them. We digged deeper into the different platforms that are designated for conducting such quantum experiments like IBM Quiskit, and superconducting platforms and computers. Further modifications and could be applied into the basics presented, for obtaining better results and integerating them into circuits.