Doctoral School of Physics - Eötvös Loránd University (ELTE)

Semester Report 4

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PhD Program: Statistical Physics, Biological Physics and Physics of Quantum Systems

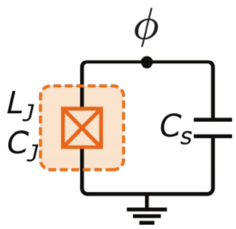
Supervisor: János Koltai

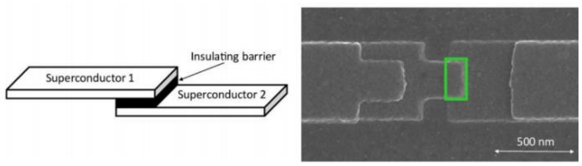
Ph.D. Thesis title: Quantum computing for superconducting qubits

Description of research work

The backbone for quantum computing is a qubit, which is a two-level system which is the bases $|0\rangle$ and $|1\rangle$. Superconducting qubits is that we engineer artificial atoms using superconducting material that can be used as a qubit. As electricity moves through the normal material it experiences resistance and this material resistance drops as temperatures get lower. But the superconductor conducts electricity without any resistance. For instance, the Aluminum which is a material that we can use to build these superconductor qubits, the critical temperature is 1.75K. To put that in perspective 1.75K is the half temperature of outer space.

There are well-defined transistors in atoms can be treated as a two-level system effectively, but most physical systems have many energy levels and the challenge we have – ideally, we want a purely two-level system. If we have a circuit with a capacitor and inductor, the energy in the circuit goes back and forth between the capacitor, it gets fully stored in the capacitor and then moves and it gets to fully stored in the inductor in the other element. Let's replace the inductor with the Josephson Junction, which is in the Figure 1 showing with box and cross. If we have two superconductors coupled by a thin insulating barrier that form a Josephson Junction. So, we have a superconductor on insulating barrier (Figure 2) in between and another superconductor. So, if there is an insulator somewhere in our circuit, that block a flow of current or electricity from one end to another. But, in this system current will actually tunnel through the insulator and then we'll continue flowing through the second superconductor. Why do we need that insulating barrier between the two pieces of superconductor? In the case, where we did not have the Josephson Junction, where we only had an inductor the problem we had was that the distance between all these energy levels were the same, so none of those distances were unique, meaning that my qubit state could easily get lost in the spectrum of all these energies, but now when we added this insulating barrier it changes the spacing between these levels (Figure 3). So, now we have a unique spacing between $|0\rangle$ and $|1\rangle$ and that allows us to use the $|0\rangle$ and $|1\rangle$ as a qubit for quantum computing.





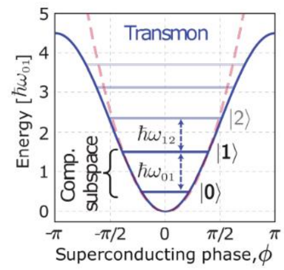


Figure 1 Figure 2 Figure 3

There is one of the examples of a superconducting qubit in figure 4, we read and operate these qubits using microwave signals that reach the qubit through either resonators or drive lines. This superconducting chip is a superconducting processor sit on the bottom of the dilution refrigerator (figure 5). The way that a dilution refrigerator work is that the fridge become gradually colder from the top to the bottom, such that at the lowest level of the fridge we typically reach temperatures of 10 mK which is roughly 500 times colder than the temperature of outer space.

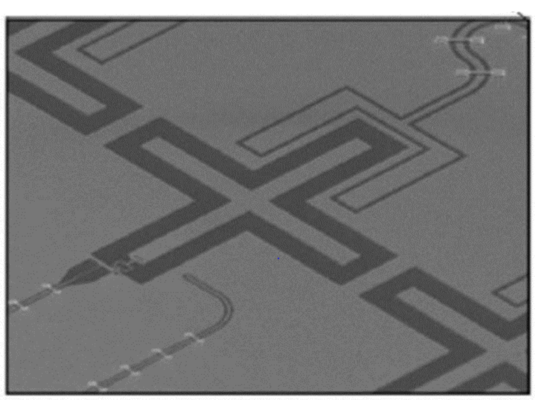


Figure 4. Superconducting qubit

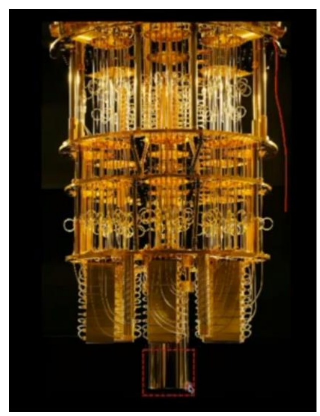


Figure 5. Dilution refrigerator

We can either engineer single-qubit and two-qubit gates for superconducting qubits using microwave pulses or natural hardware interactions. There are pros and cons of superconducting qubits. First, I want to give few examples about the pros of the superconducting qubits. One of the pros is that we can manufacture the chip and we have access to high quality gates and readout. It is compatible with existing fabrication infrastructure which means that we could use some of the techniques and tolls that have been developed for fabricating classical processor in the past 50 years to build this quantum processors. It uses microwave technology which is well developed over the past 70 years. There are some cons namely: loss to substrate material which means that since our qubits are interacting with some substrate that typically takes a toll on their coherence times and the relaxation times. They require cooling to mK temperatures to avoid accidently exciting qubits from |0⟩ and |1⟩ and as it stands with the current technology that we need bigger dilution refrigerators for the larger processors.

The ongoing research in the quantum computing field is first of all scaling to more qubits, an active area of research is achieving higher coherence times either through new designs or improvement in material that is used for building these qubits, engineer higher fidelity gates and this is all in order to achieve error correction and fault tolerance quantum computer.

There is a Qiskit which is an open-source software development kit for working with quantum computers. In my work, l have been using three main elements of Qiskit, l have building circuits and running it on real hardware in Qiskit-Terra and simulating the circuits on Qiskit-Aer and Qiskit Ignis allows us to understand and mitigate the types of errors that we see in our computations. There are two main types issue we have to deal with it which is called energy relaxation time and decoherence time. Let’s assume that we have prepared a qubit in the excited state or the |1⟩ state and if we leave the qubit in this state after a while, we find that it decays in energy and goes back to the |0⟩ state. The time scale for this error which takes us from excited state to the ground state is known as a T1. In quantum decoherence, quantum systems lose their coherence as a result of interacting with the environment over time which is known as T2 is resulted as quantum superposition turns into a classical probability distribution and lose the ability of quantum interference.

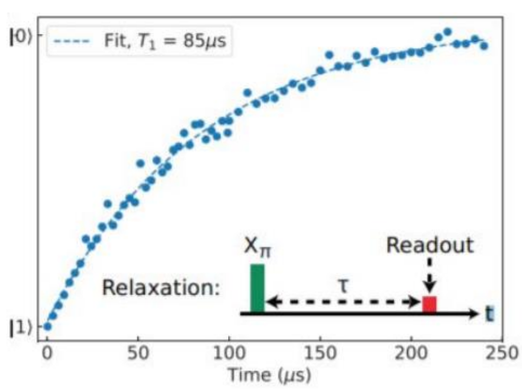


Figure 6. Relaxation time: T1

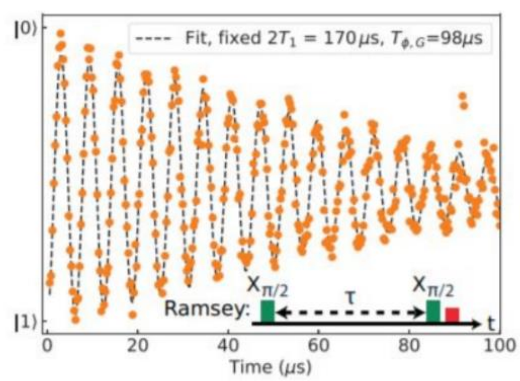


Figure 7. Decoherence time: T2

There are several other kinds of errors that we could talk about. I have worked with measurement error mitigation by preparing 6-qubits cluster state using quantum computer on the cloud by IBM which is called ibmq_16_melbourne in order to reproduce the result of an article [1] on ArXiv aimed at demonstrating quantum advantage.

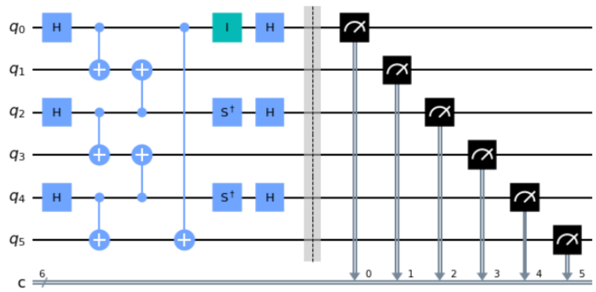
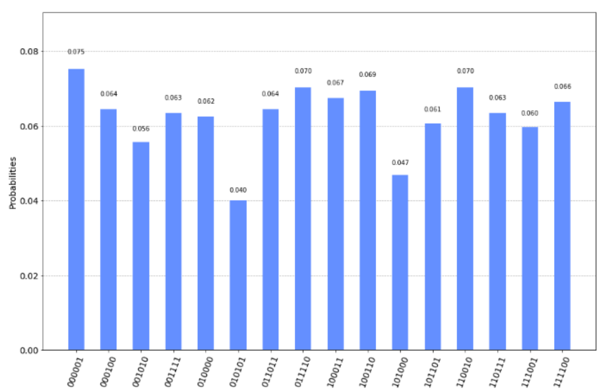


Figure 8. Optimized quantum circuit for running on noisy quantum computer

They test quantum non-local by preparing a 6-qubit cluster state using quantum computer on the cloud IBM, Ionq and Honeywell. They introduced three optimization techniques. In the case of superconducting qubits, they used the connectivity of the quantum processors to select which physical qubits are used by the quantum computer. To achieve an optimal fidelity, they selected a set of 6 neighboring qubits connected with each other in a closed loop and applied Hadamard gates on all qubits, followed by control-Z gates on neighboring qubits [2, 3], for non-neighboring qubits used intermediate SWAP or HS † gates. The second optimization consisted in using circuit identities to reduce the number of gates. The third optimization step aimed at fixing state preparation and measurement errors, by postprocessing the experimental outcomes by implemented the linear error mitigation protocol of [4]. By following those optimization steps l built up the circuit and executed it both on a simulator as well as a real quantum computer.



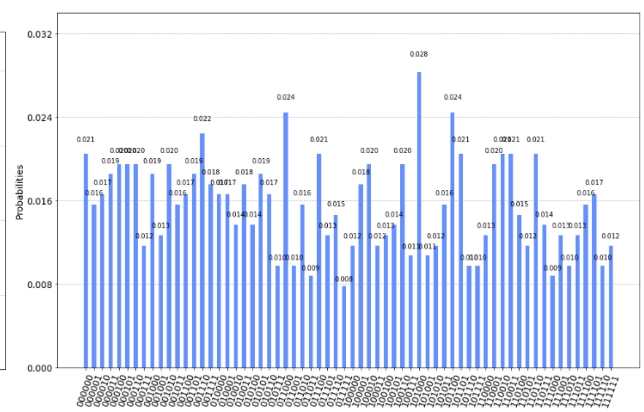


Figure 9. The result of quantum circuit on Qasm simulator *Figure 10. The result of circuit on ibmq_16_melbourne hardware*

In particular, we saw that while the simulator which simulates a perfect quantum computer, running the code on a real computer gave us small number of results in all the other states which shows the presence of error in our quantum computation. In fact, these errors are caused by various different types of noise. We can invert the results of an unknown computation and can get it as close as possible to a simulation.

Qiskit Ignis has given us a series of calibration circuits to run, in order to find out what the errors are as we run each of these circuits. In total, there are 64 of this circuits and that's expected, because we were working with a circuit that has 6 qubits. By executing the calibration circuits on the quantum hardware and took those result back and fit them we can see what parameters come of these results. By generating measurement filter which allows us to mitigate the errors in our measurement outcomes.

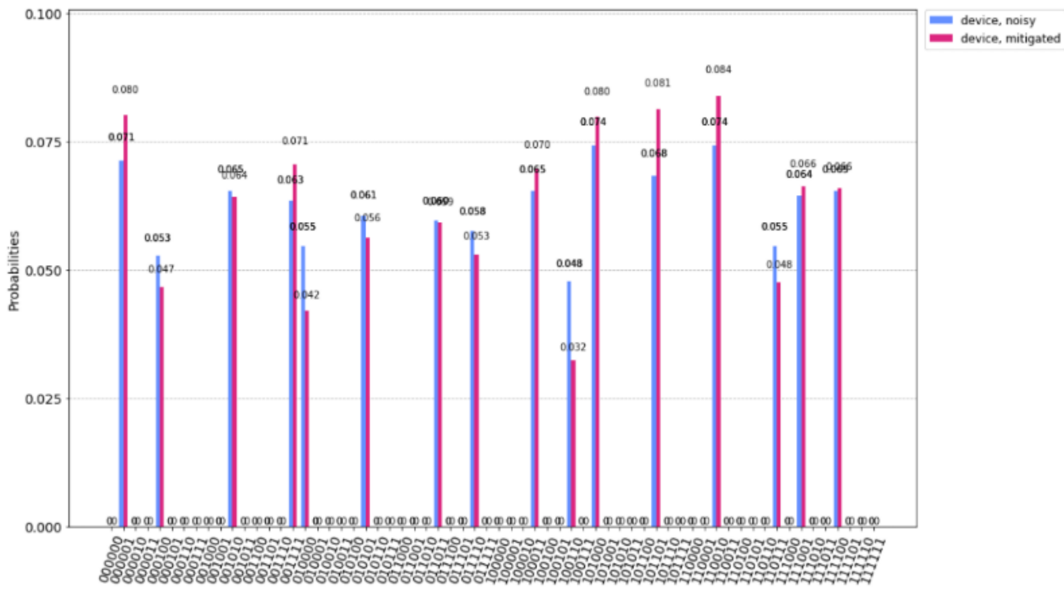


Figure 11. The result of measurement error mitigation in ibmq_16_melbourne run

So, we’ve gone from the blue chart which is the result from running our quantum circuit at the beginning on our quantum computer to the result of measurement error mitigation. The figure 11 shows that a lot of errors have disappeared here and the result looks very close to what we expect to see from a perfect simulator.

There was a task during my Qubit&Qubit class to compare the performances of three quantum computers - ibmq_5_yorktown, ibmq_belem and ibmq_16_melbourne. We quantify quantum gates using gate fidelity. One of the popular measurements of gate fidelity is randomized benchmarking protocol. Randomized refers to the fact that the circuits are generated randomly from a collection of gates. Benchmarking means that we use the results of this process to compare the performance of different systems against each other. In the lab, I perform a simplified version of randomized benchmarking to compare the performances of three quantum computers. I have created 3 qubit randomized circuit with the length 200 gates in the sequence. On the first side of the circuit, I generated the random sequence of the gates and the second part of the circuit l applied reverse or complex conjugate of gates. In fact, for a good quantum circuit we want the circuit fidelity to be larger than roughly >0.66%. l run the randomized circuits by using ibmq_5_yorktown, ibmq_belem and ibmq_16_melbourne noise models.

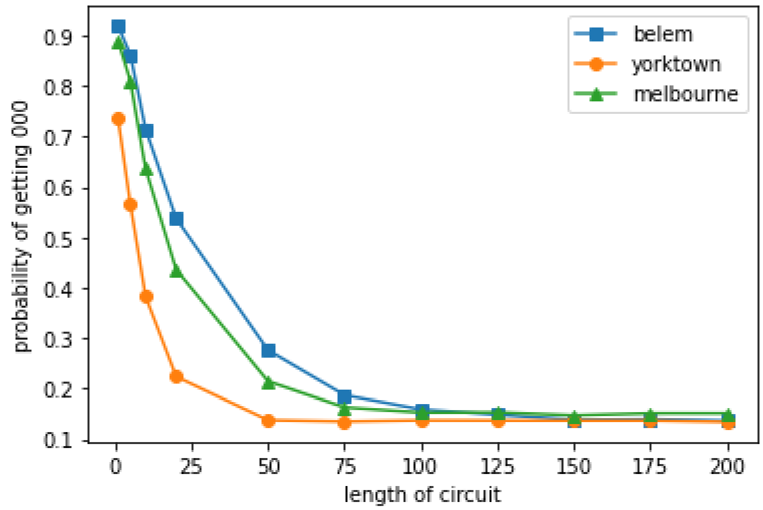


Figure 12. The result of randomized benchmarking

Perfect gates have a fidelity of 1 (100%) and in general fidelity is equal f=1-error rate. This let us, how good are gates is related to the error rate using this relation. The figure 12 shows that the ibmq_5_yorktown has 70% chance of success, ibmq_belem generally has lower error rate and higher probability of success than ibmq_16_melbourne and ibmq_5_yorktown. The graph generally goes down exponentially by the increasing the length of gates. The smaller circuit I achieve much higher of success. The graph settled down over the 0% probability, it's end off roughly above 0.1. Cause, l had here 3 qubits which means there are 8 possible measurement result and even l had total randomness one of those 8 measurement is always going to be 000 and we are going to count is a success. So, the asymptote heading down to 0.5 which is 1/8. If we had done circuits with more qubits the asymptote will be lower because the chance of success from a purely random output will be lower.

Description of educational activities carried out in the current semester

I have taken two new subjects during this semester which were: Lattice Defects II, Writing scientific papers.

Lattice Defects II – in the previous term I have studied Lattice defects I which was talking about the types of the defects, diffusion, mechanical properties of crystalline solids, general description of twinning in hexagonal crystal, dislocations and the mechanical properties. This semester I have deepen my knowledge about the dislocations, interaction between dislocations and secondary phase particles. I have studied mainly about coherent, semi-coherent and incoherent phase boundaries, dispersion strengthening. Orowan mechanism which was discovered by Hungarian physicist, dipole criterion and cutting mechanism, characterization of misorientation, macroscopic and microscopic degrees of freedom for grain boundaries, twist and tilt boundaries, physical models of grain boundaries and grain boundary segregation and etc.

Writing Scientific papers – this course taught us the methodology to write scientific paper, which included the most important steps such as the formation of abstract which should concisely describes its content and scope, how to write an effective introduction, how to review contradictory literature results, reference types. We had a task on each week to review the recent papers to analyze the content and form of title, the content of simple and structured abstract, what is the importance and function of the introduction, how would to describe the first sentence or first paragraph and last paragraph of the introduction, description of the materials and method, what is the general structure of discussion, how should be the content of conclusion and etc.

Furthermore, I follow up reading recently published scientific articles about Condensed Matter Physics and Quantum Physics regularly on https://arxiv.org/. Reporting essential articles under the scope of our team.

The Coding School's Qubit by Qubit's Introduction to Quantum Computing with IBM Quantum. The Quantum Computing was an additional course out of the university curriculum which was organized by The Coding School and IBM Quantum Computing Research. It was a first-of-its-kind course aimed at making quantum computing accessible to university students.

The full course period divided into two semesters:

Semester 1 focused on the foundational math, programming, and physics concepts necessary for quantum computing. I expanded my understandings of the Classical Computing, Quantum Computing in the Abstract, Math: Introduction to Vectors and Complex Numbers, Probability Math for Quantum Mechanics, Introduction to Python Programming and learned making measurements on circuit composer by using Gates. I have attended laboratories and seminars, submitted every assignment on weekly basis. I started to the second term of the course after successfully completing the Semester 1.

This semester I have completed the second term of the course successfully and l have got the certificate (Appendix). The second part of the above-mentioned course focused on the Quantum Mechanics, Quantum Information and Computation, and Quantum Algorithms, guided and explained me the ways using Qiskit and IBM Quantum Experience to run quantum simulations on real quantum hardware. Qiskit is an open-source software development kit for working with quantum computers at the level of pulses, circuit and application models. We were using Qiskit as a Python library in order to simulate and run quantum circuits.

Conference

CMD2020GEFES - Condensed Matter Divisions of the Spanish Royal Physics Society (RSEF-GEFES) and of the European Physical Society (EPS-CMD)

Women in Quantum Summit IV

Diversity in Quantum Computing Conference

Awards

Stipendium Hungaricum Scholarship

Hungarian Quantum Technologies Excellence Project

References

1. M.Sheffer, D.Azses, E.D.Torre. Playing quantum nonlocal games with six noisy qubits on the cloud. https://arxiv.org/pdf/2105.05266.pdf
2. K. Choo, C. W. von Keyserlingk, N. Regnault, and T. Neupert, Measurement of the entanglement spectrum of a symmetry-protected topological state using the ibm quantum computer, Physical Review Letters 121, 086808 (2018).
3. D. Azses, R. Haenel, Y. Naveh, R. Raussendorf, E. Sela, and E. G. Dalla Torre, Identification of symmetryprotected topological states on noisy quantum computers, Physical Review Letters 125, 120502 (2020).
4. S. Bravyi, S. Sheldon, A. Kandala, D. C. Mckay, and J. M. Gambetta, Mitigating measurement errors in multiqubit experiments, Phys. Rev. A 103, 042605 (2021).

Appendix

QUBIT X QUBIT

This certifies that

Natavan Gurbanova

has successfully completed Qubit by Qubit's 2020-2021

Introduction to Quantum Computing Course

sponsored by IBM Quantum

This course took place from October 2020 to May 2021. Students developed a foundational understanding of quantum computing, with topics including introductory linear algebra, coding with Qiskit, quantum mechanics, quantum algorithms, and quantum applications.

The <Coding School/>

IBM **Quantum**

Liz Durst
Director, IBM Quantum & Qiskit Community

Kiera Peltz
Executive Director, Qubit by Qubit
Founder, The Coding School