?Introduction to Quantum Computing?

Final Report of the INTEREST Program

Marius Alexandru Dragolici[a]

[a] University of Bucharest, Faculty of Physics

Abstract: The goal of the course was to explore Quantum Mechanics (QM) in a simple and intuitive way. We explored the basics of Spin Mechanics, the double-slit experiment and the Stern-Gerlach experiment, and then proceeded to study qubit measurements. We learned about quantum gates, quantum states, and finally we studied Grover's Algorithm. For the computational part of the course, we utilised the SU2 and CPX packages for performing some measurements on the HYBRILIT supercomputing platform and plotted the results using ROOT and Origin. Finally, we used IBM's qiskit platform in order to study and code quantum circuits.

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1. Spin Quantum Mechanics

The spin of an elementary particle would appear, on the surface, to be hardly different from the spin of a large, macroscopic, object. Obviously, there is far more going on here than what a simplistic picture of, let's say, a microscopic sphere spinning around an axis, can offer.

The Stern-Gerlach experiment, first performed in 1922, has long been considered the quintessential experiment that ilustrates the fact that the electron possesses intrinsic angular momentum, or how it's commonly called, spin.

The original experimental arrangement took the form of a collimated beam of silver atoms heading in the Y direction and passing through a non-uniform magnetic field directed in the Z-direction. Assuming the silver atoms posess a non-zero magnetic moment, the magnetic field will exert a torque on the magnetic dipole so that the magnetic moment vector will process about the direction of the magnetic field. This will not affect the Z component of the magnetic moment, but it will affect the X and Y components. Also, the non-uniformity of the magnetic field means that the atoms will suffer from a sideways pushing force given by the expression:

$$F_z = -\frac{\partial U}{\partial z} \qquad [1]$$

where $U = -\mu B = -\mu_z B$ is the potential energy of the silver atom in a magnetic field.

Obviously, different orientations of the magnetic vector will lead to different values of μ_z, which in turn means that there are different forces acting on the silver atoms depending on the value of μ_z.

The expectation based on classical physics is that the magnetic dipole moment vectors of the atoms will be randomly oriented in space, so there should be a continuous spread in the z component of the magnetic moments of the silver atoms. Ultimately, a line should appear on the observation screen along the Z direction. Instead, what happened was that the silver atoms arrived on the screen at only two points that corresponded to magnetic moments of

$$\mu_z = + - \mu_B \qquad [2]$$

where

$$\mu_B = \frac{eh}{2m_e} \qquad [3]$$

where μ_B is known as the Bohr Magneton.

Significance and Public Understanding: Quantum mechanics emerged as a branch of physics in the early 1900s to explain nature on the scale of atoms and led to advances such as transistors, lasers, and magnetic resonance imaging. The idea to merge quantum mechanics and information theory arose in the 1970s but garnered little attention until 1982, when physicist Richard Feynman gave a talk in which he reasoned that computing based on classical logic could not tractably process calculations describing quantum phenomena. Computing based on quantum phenomena configured to simulate other quantum phenomena, however, would not be subject to the same bottlenecks. Although this application eventually became the field of quantum simulation, it didn't spark much research activity at the time.

Correspondence: Dragolici Marius Alexandru marius.dragolici6@gmail.com 0731815245

The effects of this experiment are generally large regarding Quantum Mechanics. Regarding Quantum Computing, the main ideas to be taken from this are:

- All two level systems are equivalent to spin
- Qubits can describe electron spin
- A qubit can be measured in different bases
- Entanglement

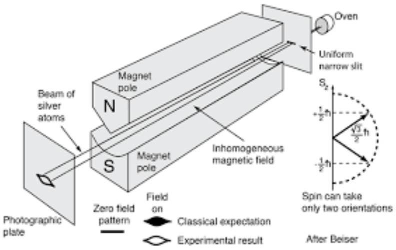

Fig. 1. Scheme of the Stern-Gerlach experiment

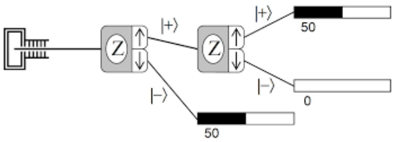

Fig. 2. Postulate of Measurement regarding Stern-Gerlach

A. A few words about the double-slit experiment. In the basic version of this experiment, a coherent light source, such as a laser beam, illuminates a plate pierced by two parallel slits, and the light passing through the slits is observed on a screen behind the plate. The wave nature of light causes the light waves passing through the two slits to interfere, producing bright and dark bands on the screen – a result that would not be expected if light consisted of classical particles. However, the light is always found to be absorbed at the screen at discrete points, as individual particles (not waves); the interference pattern appears via the varying density of these particle hits on the screen. Furthermore, versions of the experiment that include detectors at the slits find that each detected photon passes through one slit (as would a classical particle), and not through both slits (as would a wave).

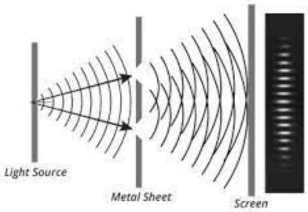

Fig. 3. Scheme of the double-slit experiment

This is important because, in the case of quantum computers:

- Qubits have wave characteristics and properties
- Qubits fall under the effects of the postulate of superposition and thus can interfere with eachother
- Interference can amplify the probability of a correct answer

2. Qubits and properties

A qubit is a two-state (or two-level) quantum-mechanical system, one of the simplest quantum systems displaying the peculiarity of quantum mechanics. In a classical system, a bit would have to be in one state or the other. However, quantum mechanics allows the qubit to be in a coherent superposition of both states simultaneously, a property that is fundamental to quantum mechanics and quantum computing.

For the purpose of this report, even though there is a multitude of implementations for a Qubit, we will only refer to the Superconducting Platform.

A. Superconduction. If mercury is cooled below 4.1 K, it loses all electric resistance. This discovery of superconductivity was followed by the observation of other metals which exhibit zero resistivity below a certain critical temperature. The fact that the resistance is zero has been demonstrated by sustaining currents in superconducting lead rings for many years with no measurable reduction. An induced current in an ordinary metal ring would decay rapidly from the dissipation of ordinary resistance, but superconducting rings had exhibited a decay constant of over a billion years!

The disappearance of electrical resistivity was modeled in terms of electron pairing in the crystal lattice by John Bardeen, Leon Cooper, and Robert Schrieffer in what is commonly called the BCS theory.

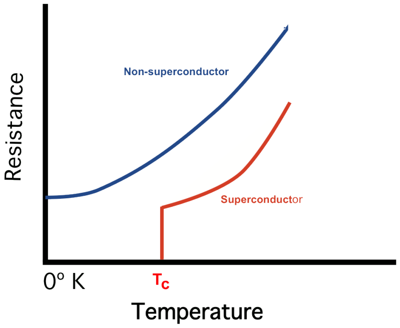

Fig. 4. Difference between a conductor and a superconductor

B. Josephson Junctions. The Josephson effect is the phenomenon of supercurrent, a current that flows continuously without any voltage applied, across a device known as a Josephson junction (JJ), which consists of two or more superconductors coupled by a weak link. The weak link can consist of a thin insulating barrier (known as a superconductor–insulator–superconductor junction, or S-I-S), a short section of non-superconducting metal (S-N-S), or a physical constriction that weakens the superconductivity at the point of contact (S-s-S).

Electronic circuits can be built from Josephson junctions, especially digital logic circuitry. Many researchers are working on building ultrafast computers using Josephson logic.

Josephson junctions can also be fashioned into circuits called SQUIDs–an acronym for superconducting quantum interference device. These devices are extremely sensitive and very useful in constructing extremely sensitive magnetometers and voltmeters.

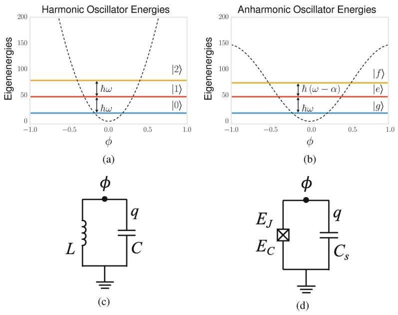

Fig. 5. Quantum phenomena in a circuit

3. Qubits and measurements

Below we describe the measurements we performed using the various platforms and packages and then we provide the processed data we obtained.

- Qubit Frequency Scan : there is a frequency at which the qubit resonates which is defined by the difference of energy between it's ground state and excited state. Even though by definition superconduction implies a large number of energy levels, it can be tweaked in order to separate low energy levels from high energy levels ones.
- Rabi Experiment : using the previously determined frequency of the qubit we can determine the strength of the π pulse. The pulse "jumps" the qubit from it's ground state to it's excited state.
- Discriminating 0 vs 1 : We find out the distribution of states in our measurements.
- Determination of the Decay Time: The application of a pulse and a time delay. We vary and repeat with incremental time delays.
- Ramsey Experiment: We first apply a $\frac{\pi}{2}$ pulse, wait and then apply another $\frac{\pi}{2}$
- Measurement of the coherence time of the qubit
- Dynamical Decoupling

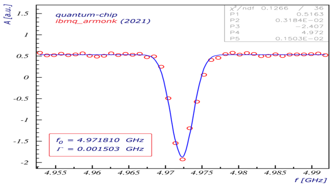

Fig. 6. Qubit Frequency Scan

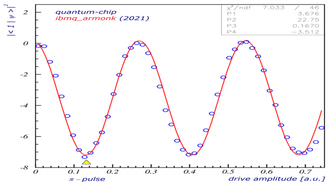

Fig. 7. Rabi Experiment

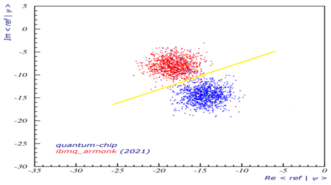

Fig. 8. Discriminating 0 vs 1

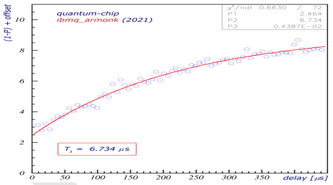

Fig. 9. Decay time

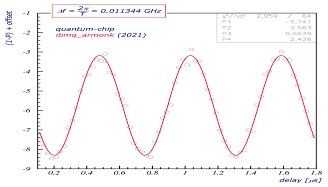

Fig. 10. Ramsey Experiment

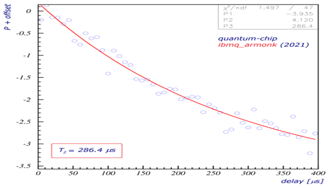

Fig. 11. Coherence Time

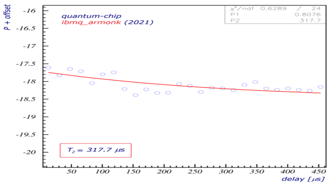

Fig. 12. Dynamical Decoupling

4. Grover's Algorithm

Grover's original paper described the algorithm as a database search algorithm, and this description is still common. The database in this analogy is a table of all of the function's outputs, indexed by the corresponding input. However, this database is not represented explicitly. Instead, an oracle is invoked to evaluate an item by its index. Reading a full database item by item and converting it into such a representation may take a lot longer than Grover's search. To account for such effects, Grover's algorithm can be viewed as solving an equation or satisfying a constraint. In such applications, the oracle is a way to check the constraint and is not related to the search algorithm. This separation usually prevents algorithmic optimizations, whereas conventional search algorithms often rely on such optimizations and avoid exhaustive search.

The major barrier to instantiating a speedup from Grover's algorithm is that the quadratic speedup achieved is too modest to overcome the large overhead of near-term quantum computers. However, later generations of fault-tolerant quantum computers with better hardware performance may be able to realize these speedups for practical instances of data.

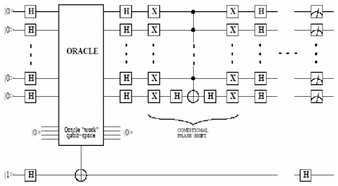

Fig. 13. Grover's Algorithm

5. Conclusions

- All two level systems are equivalent to electron spin.
- A qubit is a quantum representation of a classical bit.
- Quantum gates allow us to manipulate a qubit and change it's states.

The experience of the course in itself was a pleasant one. I got familiar with the IBM platform and learned a lot about the future of cumputing.