How to test if quantum theory is correct?

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Abstract
Via an envelope analogy we illustrated photon polarization and hence deduced Bell's inequalities. According to non-quantum physics, those have to be satisfied. Afterwards we showed in a quantum computer environment that the inequality is actually being violated.

1. Introduction

In the early 20th century, there were two opinions about quantum theory. One of them supposed that all of quantum mechanics is unpredictable and we can only know the probability of some phenomena, and the second supposed that we will be able to calculate some of the quantum phenomena in the same way as any other phenomenon. Bell came up with inequalities, those have to be satisfied to prove that the second opinion is correct. Quantum systems, such as in quantum computers, can however violate this inequality. To prove that the first opinion is correct we did experiments simulating photon diffraction using quantum computers for studying violations of Bell's inequality. We measured the probability of two photons having the same polarization after diffraction and passing through a polarizer.

2. The Envelope Analogy

Let there be a big envelope (photon source) containing two medium-size envelopes (photon streams) - each containing 3 papers (photons). Each of them has blue/red dot (binary 0/1) on it, representing polarization plane directions. Respective papers' dots are anti-correlated, i.e. is always the opposite color.

We distribute the medium-sized envelopes to two observers, **A**lice and **B**ob. They both choose a random paper from their envelopes. Due to the rules of the papers' generation, we can distinguish several scenarios:

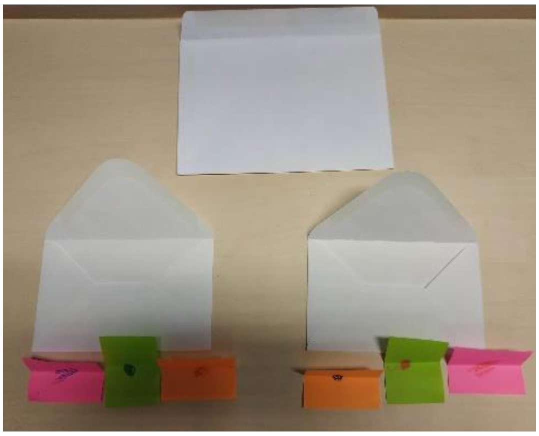

Fig. № 1: The envelopes

Scenario	Paper A	Paper B	Likelihood
№ 1	B B B	R R R	W_1
№ 2	B B R	R R B	W_2
№ 3	B R B	R B R	W_3
№ 4	B R R	R B B	W_4

$$W_n \geq 0$$
$$\sum W_n = 1$$

Fig. № 2: Scenarios

Now, let p(nx, my) be the probability of Alice finding a color x dot on the n-th paper and Bob finding a color y dot on the m-th paper or vice versa.
An instance of Bell's inequality:

$$p(1r, 2r) + p(1r, 3r) \geq p(2r, 3r)$$

Substituting:

$$p(1r, 2r) = \frac{1}{18}(W_3 + W_4)$$

$$p(1r, 3r) = \frac{1}{18}(W_2 + W_4)$$

$$p(2r, 3r) = \frac{1}{18}(W_2 + W_3)$$

Results in:

$$\frac{1}{18}[(W_3 + W_4) + (W_2 + W_4)] \geq \frac{1}{18}(W_2 + W_3)$$

Yielding:

$$2W_4 \geq 0$$

Which was initially given.

3. Experiment

3.1 Setup

We used IBM's quantum computer in Melbourne to study violations of Bell's inequalities. The specific qubits used were pairs 0, 1 and 12, 13 – the qubits with the lowest error rate at the time of measurement (Figure № 3) – using a sample size of 8192 shots per measurement. The code used involved testing different polarizer angles, specifically 0, π/4 and 3π/4 radians (Figure № 4). First, a simulated pair of photons, represented by the qubits, is released. Each simulated photon then passes through one of these polarizers and is measured. The measurements show us the probability of the simulated photons having equal polarization. We estimated the probability using the frequency of the phenomenon. These probabilities serve as input for Bell's inequality to show us whether a violation has occurred. And if Bell's inequality is violated in a quantum environment, quantum theory predictions are correct.

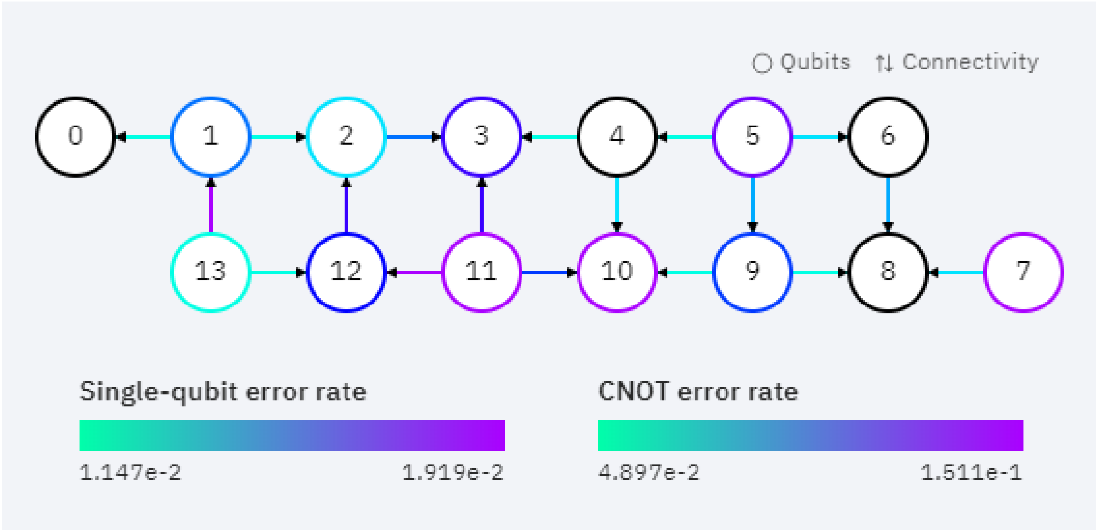

Fig. № 3: Qubit error rate

Circuit editor

```
OPENQASM 2.0;
include "qelib1.inc";
qreg qubits[14];  // our qubits
creg memory[14];  // regular bits
x qubits[12];     // write 1
x qubits[13];     // write 1
h qubits[13];     // superposition 0-1
cx qubits[13],qubits[12]; // if qubits[13] is 1, flip qubits[12]
  // => now they are intertwined

h qubits[13]; // "rotation
t qubits[13]; // in an abstract
h qubits[13]; // space"
measure qubits[12] -> memory[12]; // measure
measure qubits[13] -> memory[13]; // measure
```

Fig. № 4: our IBMQ program

3.2 Results

We defined the variable Q by the ratio of the right-hand and left-hand side of Bell's inequality:

$$p(\alpha_0, \beta_0) + p(\beta_0, \gamma_0) \geq p(\alpha_0, \gamma_0)$$

$$Q = \frac{p(\alpha_0, \gamma_0)}{p(\alpha_0, \beta_0) + p(\beta_0, \gamma_0)}$$

Where α, β, γ represent the various angles of the polarizers, and α_0, β_0, γ_0 represent the polarization of the photons after passing through the polarizers. Analyzing results from different qubits we found multiple values of Q (Figure № 5).

Measurement #	**1**	**2**	**3**	**4**
Q	1,349	1,224	1,127	1,086

Fig. № 5: Experiment outcomes

Since the value of Q was greater than 1 in all cases, a violation of Bell's inequality occurred every time. We also looked at the differences produced by horizontal and vertical polarization and found that a violation only occurred with one of them.

4. Conclusion

We have constructed an experiment on IBM's quantum computer that simulates the state of polarized photons with detectors. When executed, the data shows the system violates Bell's inequalities. Altogether this proves that quantum systems can violate the Bell's inequality. To genuinely demonstrate quantum physics predictions are valid, the two qubits used in this experiment would need to be far away.

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