QIP Course 12: Refuting the local realism view of the universe

Ryutaroh Matsumoto

Nagoya University, Japan
Send your comments to ryutaroh.matsumoto@nagoya-u.jp

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@ Tokyo Tech.

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Implicit assumption in the classical physics

1. The real nature of the universe can be completely described by mathematics, and the complete description of an object at a time t allows deterministic prediction of its future trajectory.
2. Effects of an event cannot propagate instantaneously to another place.

The latter is called the locality. Without it everything could interact with everything in the universe, and it would be hopeless to have some theories to predict the future.

The former is called the realism. The purpose of this unit is to explain how to verify whether or not both claims hold simultaneously. It is experimentally confirmed that at least one of them is false.

CHSH inequality

by John Clauser, Michael Horne, Abner Shimony, and Richard Holt in 1969, based on the paper by John Stewart Bell who died when he was nominated a Nobel prize for the work explained today.

Suppose there are two observers Alice and Bob. They measure the photon polarizations by slits, and map pass/absorption to $+1$ or -1. Alice uses two kinds of directions of slits, and outcomes (± 1) are denoted by the random variable A for one direction and A' for the other.
Similarly, Bob uses two kinds of directions of slits, and outcomes (± 1) are denoted by the random variable B for one direction and B' for the other.

Assuming the realism

If there is a complete description of the physical reality, independent of which measurements are made, then there must exist a definite value of B' even when the slit direction for B is used and a value of B is recorded. This realism assumption implies

- Either $B - B'$ or $B + B'$ is zero, and
- the other is ± 2.

From the above, we have

$$S = AB + A'B + AB' - A'B' = A(B + B') + A'(B - B') \leq 2. \quad (1)$$

How to perform an experiment

- Each photon pair must arrive at slits of Alice and Bob almost simultaneously so that they can exclude the possibility of a photon being affected by the measurement outcome of the other.
- Alice and Bob choose their slit directions
  - after each photon pair is generated, otherwise we cannot exclude the possibility that the photon generator makes $AB = A'B = AB' = -A'B' = 1$ and $S > 2$,
  - before the effect of the measurement outcome of the opposite side could reach, otherwise we cannot exclude the possibility that the random slit selection is somehow affected by the measurement outcome of the opposite side.

Checking CHSH value

Performing the experiment and compute the sample average of the random variable S. If both realism and locality (effects cannot propagate faster than light) are true, then the sample average of S must be ≤ 2.
On the other hand, when the quantum state of the pair of photons is

$$\frac{1}{\sqrt{2}}(|+\rangle|-\rangle - |-\rangle|+\rangle),$$

where $|+\rangle$ ($|-\rangle$) is the eigenvector of X belonging to eigenvalue $+1$ (-1), and A corresponds to the observable Z, A' does to X, B does to $-(Z+X)/\sqrt{2}$, and B' does to $(Z-X)/\sqrt{2}$, the sample average of S becomes

$$2\sqrt{2}. \tag{2}$$

Most of experimental results support the quantum theory so far.

- Bell thought that experiments would support the local realism until the first experimental report was provided.
- Bell thought the locality instead of the reality should be discarded.

Source: `http://en.wikipedia.org/wiki/John_Stewart_Bell`

Homework for getting the course credit

Send a PDF file to ryutaroh.matsumoto@nagoya-u.jp, by 14 September 2017. When your report has an incorrect answer, your will be notified of your error and have an oppotunity to revise your report. Please write the detail of your computations.

1. Verify (2). This is optional. You can get the score 100 without solving this.
2. Solve Q4 of the 10th handout with $x = 4$. Other values are the same. (33 points)
3. Solve Q5 of the 10th handout with $x = 4$. Other values are the same. (33 points)
4. Solve Q6 of the 10th handout with $x = 4$. Other values are the same. (34 points)