Aalto University
LC-1117 - Integrated Oral and Written Skills

Introduction to Bell inequality and experiments

Jonni Järvinen

1 Introduction

It has arguably become common knowledge that current theories cannot fully describe quantum mechanics, and that their disconnect from classical mechanics is significant. This disconnect was pioneered by Werner Heisenberg with his uncertainty principle in 1927 and further reinforced in 1964 by John Stewart Bell in his article titled 'On the Einstein Podolsky Rosen paradox' in which he introduced the Bell inequalities [1]. Before this article, it was suggested that states such as the spin of particles are pre-determined by hidden variables which can be thought of as unobservable instructions for a particle to behave in a certain way when measured [2]. These types of local hidden variable theories were present during early interpretations of quantum mechanics. The purpose of this essay is to familiarize the reader with the experiments derived from Bell's article.

2 Bell's article

In his article, Bell derives an inequality using classical mechanics and mathematics about the probabilities of certain measurable characteristics of particles [3]. Bell argues that, in a universe where the hidden variables exist, this inequality would apply to all particles. However, using quantum mechanics Bell proposes an experiment that, if conducted, would yield different results than the theory predicts thus violating the inequality and disproving the hidden variable theory altogether. Bell's article concludes by stating that despite his findings, there must be some mechanism by which the measurement of one particle can instantaneously affect the measurements of another regardless of distance.

3 The first Bell tests

The first Bell test was conducted by John Clauser and Stuart Freedman in 1972 [4]. The inequality has been proven to be extremely accurate by subsequent tests, arguably most notable of which was conducted by Alain Aspect et al. in 1982. In their experiment, Aspect and his team utilized polarization analyzers whose orientations could be changed nearly instantly. The orientation of these analyzers was changed while the photons they investigated had already been emitted from the source such that no information traveling at light speed could be exchanged by the photons. The team noticed that these changes did not have an effect on the measured properties of the photons, thus closing a proposed loophole suggesting that the measuring equipment may sway the results.

4 Loopholes in Bell tests

The locality loophole closed by Aspect was not the only loophole involved with the Bell tests. One of the major loopholes is that of detection efficiency which proposes that the results may not be accurate due to the fact that not all photons can be detected in optical experiments [5]. This can be circumvented by conducting a non-optical experiment and/or using equipment that can detect the particles more efficiently. Another loophole involves the fact that in nearly all Bell tests multiple measures are made in the same pair of locations. One can argue with locality that measurements of new particles can be affected by the particles previously measured in that location, thus leading to correlation between measurements.

5 Conclusion

An excessive number of Bell experiments have disproven local hidden variable theories, but the full implications of Bell's theorem for quantum mechanics are yet to be discovered [5]. It has been proven that entangled particles cannot be used for transferring information instantaneously. However, research in this field may give a better understanding of the universe or even form an entirely new branch of physics. One can only wait to see what subsequent experiments can offer.

References

[1] Appleby, D.M. Quantum Errors and Disturbances: Response to Busch, Lahti and Werner. Entropy 2016, 18, 174. <https://doi.org/10.3390/e18050174>

[2] Press release. NobelPrize.org. Nobel Prize Outreach AB 2023. Sun. 28 May 2023. <https://www.nobelprize.org/prizes/physics/2022/press-release/>

[3] Bell, J.S. On the Einstein Podolsky Rosen paradox. Physics Vol. 1, No. 3, pp. 195—200, 1964

[4] Freire Junior, O. Alain Aspect's experiments on Bell's theorem: a turning point in the history of the research on the foundations of quantum mechanics. Eur. Phys. J. D 76, 248 (2022). <https://doi.org/10.1140/epjd/s10053-022-00542-z>

[5] "Physics:Loopholes in Bell tests." HandWiki, . 29 Oct 2022. 28 May 2023 `<https://handwiki.org/wiki/index.php?title=Physics:Loopholes_in_Bell_tests&oldid=2338563>`