Template Report about Bell’s Inequality (at DTU)

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# EPR Paradox

The Einstein–Podolsky–Rosen paradox (EPR paradox) is a [thought experiment](https://en.wikipedia.org/wiki/Thought_experiment) proposed by physicists [Albert Einstein](https://en.wikipedia.org/wiki/Albert_Einstein), [Boris Podolsky](https://en.wikipedia.org/wiki/Boris_Podolsky) and [Nathan Rosen](https://en.wikipedia.org/wiki/Nathan_Rosen) (EPR) that they interpreted as indicating that the explanation of physical reality provided by [quantum mechanics](https://en.wikipedia.org/wiki/Quantum_mechanics) was incomplete. In a 1935 paper titled Can

Quantum-Mechanical Description of Physical Reality be Considered Complete, they attempted to mathematically show that the [wave function](https://en.wikipedia.org/wiki/Wave_function) does not contain complete information about physical reality, and hence the [Copenhagen interpretation](https://en.wikipedia.org/wiki/Copenhagen_interpretation) is unsatisfactory; resolutions of the paradox have important implications for the [interpretation of quantum mechanics](https://en.wikipedia.org/wiki/Interpretation_of_quantum_mechanics).

<https://en.wikipedia.org/wiki/EPR_paradox>

# Bell inequality / CHSH inequality

Bell’s theorem is a theorem of inequality that addressed the concerns of the EPR paradox. [John Stewart Bell](https://en.wikipedia.org/wiki/John_Stewart_Bell) was intrigued by the argument given and in favor of [hidden variable theories](https://en.wikipedia.org/wiki/Hidden_variable_theories) creating his inequality to disprove [Von Neumann](https://en.wikipedia.org/wiki/John_von_Neumann)'s proof that a hidden-variable theory could not exist. However, he discovered something new by rephrasing the problem as to whether Quantum Mechanics was correct and

non-local (showed Entanglement), or whether Quantum Mechanics was incorrect because Entanglement did not exist. Contrary to popular opinion, Bell did not prove hidden variable theories could not exist, but he proved they had to have certain constraints upon them especially that Entanglement was necessary. These non-local hidden variable theories are at variance with [The Copenhagen Interpretation](https://en.wikipedia.org/wiki/The_Copenhagen_Interpretation) in which Bohr famously stated, “There is no Quantum World.” and in which, the measurement instrument is differentiated from the quantum effects being observed. This has been called The [Measurement problem](https://en.wikipedia.org/wiki/Measurement_problem) and the [Observer effect](https://en.wikipedia.org/wiki/Observer_effect_(physics)) problem.

The CHSH inequality can be used in the proof of [Bell's theorem](https://en.wikipedia.org/wiki/Bell%27s_theorem), which states that certain consequences of [entanglement](https://en.wikipedia.org/wiki/Quantum_entanglement) in [quantum mechanics](https://en.wikipedia.org/wiki/Quantum_mechanics) cannot be reproduced by [local hidden variable theories](https://en.wikipedia.org/wiki/Local_hidden_variable_theory). Experimental verification of violation of the inequalities is seen as [experimental confirmation](https://en.wikipedia.org/wiki/Experimental_confirmation) that nature cannot be described by local [hidden variables theories](https://en.wikipedia.org/wiki/Hidden_variable_theories). CHSH stands for [John Clauser](https://en.wikipedia.org/wiki/John_Clauser), Michael Horne, [Abner Shimony](https://en.wikipedia.org/wiki/Abner_Shimony), and [Richard Holt](https://en.wikipedia.org/w/index.php?title=Richard_Holt_(physicist)&action=edit&redlink=1). They derived the CHSH inequality, which, as with [John Bell's](https://en.wikipedia.org/wiki/John_Stewart_Bell) original inequality (Bell, 1964), is a constraint on the statistics of

"coincidences" in a [Bell test experiment](https://en.wikipedia.org/wiki/Bell_test_experiments) which is necessarily true if there exist underlying local hidden variables ([local realism](https://en.wikipedia.org/wiki/Local_realism)). This constraint can, on the other hand, be infringed by quantum mechanics.

<https://en.wikipedia.org/wiki/Bell%27s_theorem> <https://en.wikipedia.org/wiki/CHSH_inequality>

The Bell inequality goes as follows:

− 2 ≤ *E*(α, β) −

*E*(α, β′)

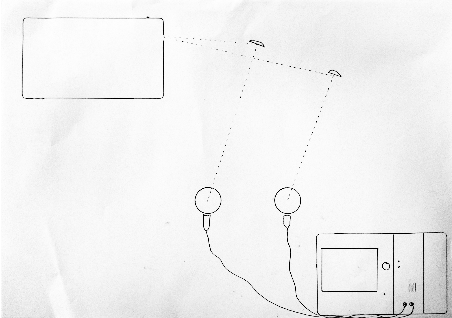
+ *E*(α′, β)

+ *E*(α′, β′) ≤ 2

Which means that no random system can have a correlation that is bigger than 2 or less than -2.

# The experiment

This is how the setup looked like:



In the top, there is a box containing the laser and the beam splitter. When the photons come outside of the box, they are entangled because of a really thin crystal at the end of the box.

The light then passes some mirrors for an easier setup, before it eventually comes to the interesting part, the polarisation filters. Depending on the photons polarization, it can either pass or not pass. Before the filter, both photons were in a superposition. As the first photon passes the polarisation filter, the waveform collapses and both photons will have the same state. Behind the polarisation filter, there is a fiber optics cable going to a measurement device that can measure which of the photons went through the polarisation filters.

# Measurements and calculations

We measured the photons to calculate the S-value for the Bell inequality:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Polarisation Angle** | | **single 0** | **single 1** | **coincidence 01** | **expected false** | **corrected** |
| α (#0) | β (#1) | N0 | N1 | N | Nac | N – Nac |
| 0 (H) | 22.5 | 105573 | 84516 | 5026 | 223 | 4803 |
| 0 (H) | 67.5 | 106019 | 69297 | 1102 | 184 | 918 |
| 0 (H) | 112.5 | 106772 | 72163 | 919 | 193 | 726 |
| 0 (H) | 157.5 | 106668 | 78995 | 4191 | 211 | 3980 |
| 315 (-) | 22.5 | 91541 | 85016 | 1504 | 195 | 1309 |
| 315 (-) | 67.5 | 92061 | 69515 | 595 | 160 | 435 |
| 315 (-) | 112.5 | 95650 | 73187 | 3466 | 175 | 3291 |
| 315 (-) | 157.5 | 94384 | 80613 | 3913 | 190 | 3723 |
| 90 (V) | 22.5 | 81767 | 85001 | 604 | 174 | 430 |
| 90 (V) | 67.5 | 82680 | 70003 | 2489 | 145 | 2344 |
| 90 (V) | 112.5 | 85123 | 73282 | 2805 | 156 | 2649 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| 90 (V) | 157.5 | 88846 | 84397 | 774 | 187 | 587 |
| 45 (+) | 22.5 | 94832 | 84752 | 4087 | 201 | 3886 |
| 45 (+) | 67.5 | 95096 | 68901 | 3406 | 164 | 3242 |
| 45 (+) | 112.5 | 97818 | 73742 | 678 | 180 | 498 |
| 45 (+) | 157.5 | 96832 | 80130 | 1035 | 194 | 841 |

Using this data, we can calculate the S-value as follows:

*E*(α, β) ≈ 0, 6903

*E*(α, β′)

*E*(α′, β)

*E*(α′, β′)

≈ − 0, 5977

≈ 0, 6155

≈ 0, 7314

*S* = *E*(α, β)

− *E*(α, β′)

+ *E*(α′, β)

+ *E*(α′, β′)

≈ 2, 6349

Bell’s inequality is true in our measurements, which means that the principle of realism or locality can’t be true for entangled quantums.

# Final conclusion

Even though our measurements clearly show that Bell’s inequality is true, there are some loopholes that due to the nature of the semi-professional setup remain open. It is expected that in the next few years there will be an experiment closing all loopholes at the same time.