Can violations of Bell’s inequalities be considered as the final proof of quantum physics?

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Plan of the presentation

• **Part 1**  Semi-classical, heuristic interpretation of modern J. Bell’s experiments

• **Part 2**  A quick look behind – Revisiting the Science story
Can violations of Bell’s inequalities be considered as the final proof of quantum physics?

Sketch of modern Bell’s experiments

- Measure correlations between the four detectors when varying PBS angles $\alpha$ and $\beta$
Semi-classical interpretation

- Assume a “hidden rule” stating that photon polarization states are opposite at their creation. Orientations of linearly polarized photons n°1 and 2 are \([ \lambda, -\lambda] \)
- Complies with the conservation law of cinematic momentum
Can violations of Bell’s inequalities be considered as the final proof of quantum physics?

**Equivalence with Quantum Physics**

- **Joint detection probabilities between couples of detectors:**

  \[
  \begin{align*}
  [D1^+, D2^+] \rightarrow P_{++} &= \frac{\int_{0}^{2\pi} \cos(\alpha - \lambda) \cos(\beta - \lambda) \, d\lambda}{2\pi} = \frac{\cos^2(\alpha - \beta)}{4} \\
  [D1^-, D2^-] \rightarrow P_{--} &= \frac{\int_{0}^{2\pi} \sin(\alpha - \lambda) \sin(\beta - \lambda) \, d\lambda}{2\pi} = \frac{\cos^2(\alpha - \beta)}{4} \\
  [D1^+, D2^-] \rightarrow P_{+-} &= \frac{\int_{0}^{2\pi} \cos(\alpha - \lambda) \sin(\beta - \lambda) \, d\lambda}{2\pi} = \frac{\sin^2(\alpha - \beta)}{4} \\
  [D1^-, D2^+] \rightarrow P_{-+} &= \frac{\int_{0}^{2\pi} \sin(\alpha - \lambda) \cos(\beta - \lambda) \, d\lambda}{2\pi} = \frac{\sin^2(\alpha - \beta)}{4}
  \end{align*}
  \]

- **Correlation coefficient:**

  \[
  E(\alpha, \beta) = \frac{P_{++} + P_{--} - P_{+-} - P_{-+}}{P_{++} + P_{--} + P_{+-} + P_{-+}} = \cos 2(\alpha - \beta)
  \]

- **Complies with Quantum Physics – Allows violation of Bell's inequalities**
Can violations of Bell’s inequalities be considered as the final proof of quantum physics?

Are Bell’s inequalities applicable here?

- Bell’s inequalities writes:
  \[-2 \leq S(\alpha, \beta, \alpha', \beta') = E(\alpha, \beta) - E(\alpha, \beta') + E(\alpha', \beta) + E(\alpha', \beta') \leq +2\]

- No reason that \(\lambda\) stays common for each couple \((\alpha, \beta)\) and \((\alpha', \beta')\) because measurements are not simultaneous.
The EPR paradox (1/2)


- **Definitions:**
  - **Physical reality:** A parameter measurable from an experimental apparatus without disturbing it, and predictable by a physical theory
  - **Completeness:** A theory taking into account all elements of physical reality

- Quantum Mechanics are based on Heisenberg’s Uncertainty Principle. Do they give a complete view of physical reality?
  1) **If No,** a more complete theory may exist
  2) **If Yes,** we must accept the Uncertainty Principle and sacrifice our usual understanding of objective physical reality

- To decide between hypotheses n°1 and 2, EPR described a *Gedanken* experiment
The EPR paradox (2/2)


- The EPR *Gedanken* experiment is based on intricated particles — Not necessarily photons
- It shows that some elements of physical reality (here the position and momentum of particles) can be determined simultaneously
- This contradicts hypothesis n°2, hence only hypothesis n°1 is valid and Quantum Mechanics are not complete
- It finally seems that **the main purpose of EPR was to defeat the Uncertainty Principle**
- Additional remarks:
  - The paper strictly follows the formalism of Quantum Mechanics
  - No "modern" considerations about causality, non-locality, propagation of information faster than the speed of light, or hidden variables
Answer from N. Bohr


- EPR paradox was not the first attack against the Uncertainty Principle
- In his answer, N. Bohr essentially discusses two previous Einstein’s ‘s *Gedanken* experiments involving photons only
- He also suggests that intricated particles should be considered as a single global system instead of two independent systems (→ Non locality ?)


San Diego, 08-28-13
D. Bohm's interpretation


- New interpretation of the EPR paradox, based on contemporary quantum formalism
- Measurements performed on spinned atoms should be equivalent to those of position and momentum of particles
- No instantaneous “hidden interaction” between atoms can exist – This would violate the laws of special relativity
- Spinned atoms experiment could be simplified by measuring correlations between polarizations of intricated photons
- **NOTA**: In earlier papers (1952), Bohm firstly mentioned the possibility of “hidden variables”. But he abandoned this idea in his 1957 paper
Bell's inequalities


- Following Bohm’s ideas, Bell evoked experiments based on spinned particles – not photons – and Stern-Gerlach magnets detectors
- There exists a huge quantity of Bell's inequalities. Here we used the Clauser, Horne, Shimony and Holt (CHSH) form:

\[-2 \leq S(\alpha, \beta, \alpha', \beta') = E(\alpha, \beta) - E(\alpha, \beta') + E(\alpha', \beta) + E(\alpha', \beta') \leq +2\]

- CHSH finally defined modern setups for testing Bell’s inequalities from photon polarization states, and four different polarizer angles
- Later, the violation of Bell’s inequalities was experimentally demonstrated by Aspect et al, Weihs et al, and followers
- This is currently considered as the ultimate proof of Quantum Physics completeness, but…
Conclusion

• We proposed a semi-classical model explaining the violation of Bell’s inequalities in modern experiments based on photons polarization.

• But these experiments do not seem to respect the original spirit of EPR paper, that consists in measuring position and momentum of any type of particle.

• The EPR paradox should be considered as the 3rd and last attack from Einstein against Heisenberg’s Uncertainty Principle.

• A final proof of the completeness of quantum physics theory remains to be demonstrated.