

BRK-009 · Quantum foundations become experimentally discriminable

BRK · Conceptual Breaks

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Two accounts of nature may reproduce many of the same observations and nevertheless disagree about a carefully chosen combination of measurements. Bell's work made such a disagreement explicit for quantum correlations. A debate about whether quantum mechanics needed a more complete account of individual events acquired a mathematical constraint that experiments could test.

The break was not the discovery that all philosophical questions had become laboratory questions. It was narrower and more powerful: particular assumptions about locally produced outcomes imply restrictions on observable correlations. Quantum mechanics predicts violations of those restrictions. The assumptions, the statistical prediction and the experimental implementation can therefore be examined separately.

1. Correlation alone was never enough

Ordinary correlated objects do not establish a quantum mystery. Two envelopes can contain opposite answers fixed when they were prepared. Opening one then reveals what the other contains, without changing anything at the distant location. Observing opposite outcomes is compatible with this account.

The difficulty arises when investigators can choose different measurements after preparing a pair. A proposed local explana-

tion must reproduce the correlations across all the relevant combinations of choices, not just one convenient combination. Bell's 1964 paper formulated this difficulty for the singlet state of two spin-one-half particles. [1]

Bell did not prove that every theory with additional variables was impossible. His paper explicitly discusses a nonlocal hidden-variable account. What matters is the conjunction of assumptions being tested. Treating the result as a ban on thinking about an underlying physical account erases the structure of the theorem.

2. A restriction that can be calculated

A useful later form is the CHSH inequality, named for Clauser, Horne, Shimony and Holt, whose 1969 paper connected Bell's result to realizable experiments. Suppose each side has two possible measurement settings and each recorded outcome is either +1 or -1. Write the outcomes assigned by a local deterministic model as A, A', B and B' . [2]

For one assignment, consider $A(B + B') + A'(B - B')$. Because B and B' are each ± 1 , one parenthesis is zero and the other is ± 2 . The expression must therefore be +2 or -2. Averaging over assignments gives an absolute bound of 2 on the corresponding combination of correlations.

This short calculation is a modern explanatory version of the bound, not a transcription of Bell's 1964 derivation. It also reveals an important assumption: the same distribution of underlying states is used when averaging the different setting combinations. If that distribution depends on the measurement choices in an unrestricted way, the argument no longer establishes this bound.

Local stochastic models can be included by representing their additional randomness in the underlying specification. The result

is not rescued merely by replacing deterministic instructions with local probabilities. However, the precise conditions still matter: locality, the independence assumptions relating preparation and choices, and the handling of recorded events must be stated.

3. Why quantum predictions make the bound interesting

For suitable measurements on an entangled pair, quantum mechanics predicts a CHSH magnitude of $2\sqrt{2}$, approximately 2.828. The distinction between that value and 2 gives the experiment something definite to discriminate. It is not a demand that one laboratory somehow observe four incompatible measurements on the same particle at once.

Instead, many trials use different pairs of settings. The observed correlations are assembled from those trials. For this assembly to test the intended inequality, the rules selecting and classifying trials must not manufacture a favorable subset. The mathematical bound and the practical rules for constructing the sample belong in the same explanation.

A violation rules against the stated local model class under the experimental assumptions. It does not select a unique interpretation of quantum mechanics. Nor does it identify a controllable message sent from one station to the other. Strong correlations in joint results and an ability to choose the distant marginal result are different claims.

4. Experimental improvements change which objections remain

Aspect, Dalibard and Roger's 1982 experiment used analyzers that switched during the photons' flight. This addressed the concern that settings fixed sufficiently early could permit ordinary commu-

nication to coordinate outcomes. The experiment was a substantial step, but its design should not be retrospectively described as closing every experimental loophole. [3]

Detection efficiency presents another difficulty. If only a subset of emitted pairs is observed, an explanation might exploit differences between detected and undetected events. A locality control does not automatically solve a detection problem. Conversely, highly efficient detection does not automatically establish sufficient spacetime separation.

In 2015, Hensen and colleagues reported a Bell inequality violation using electron spins separated by 1.3 kilometers, combining controls on the major locality and detection loopholes in one experiment. The published claim concerns a statistical test with a finite sample, not a logical impossibility established by one pair of outcomes. [4]

Calling an experiment “loophole-free” is consequently shorthand with a defined scope. No experiment eliminates the need to trust every feature of its operation, and no such label makes unrestricted correlations between measurement choices and hidden variables experimentally impossible. The strength of the result lies in explicit controls and quantified inference, not in an exemption from assumptions.

5. The change in what counted as a scientific dispute

An underlying account could once appear protected by the claim that its variables were unobservable. Bell-type reasoning shows why that protection can fail. The variables need not be observed individually if the proposed structure constrains the statistics of accessible outcomes. Unobservability of a mechanism does not guarantee observational equivalence of theories.

The converse is equally important. A disagreement between interpretations does not automatically imply a different experimental prediction. If two accounts reproduce the same relevant probabilities, this class of experiment does not distinguish them.

Describing every interpretation as either refuted or confirmed by Bell tests makes the evidence claim more than it can support.

The historical achievement was a sequence of transformations: a conceptual question became an inequality, an inequality became an experimental design, and experimental weaknesses became targets for new designs. Neither the mathematics alone nor the instruments alone completed the transition. The lasting result is a more precise account of which assumptions can survive together when confronted with measured correlations.

Related reading

BRK Article 008, “Testing gravity: 1915 to 1975,” examines how common comparison frameworks let experiments distinguish theories that share many successful predictions.

References

- [1] Bell, J. S. “On the Einstein Podolsky Rosen Paradox.” *Physics Physique Fizika* 1, 195–200 (1964). <https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195>
- [2] Clauser, J. F., Horne, M. A., Shimony, A., and Holt, R. A. “Proposed Experiment to Test Local Hidden-Variable Theories.” *Physical Review Letters* 23, 880–884 (1969). <https://doi.org/10.1103/PhysRevLett.23.880>
- [3] Aspect, A., Dalibard, J., and Roger, G. “Experimental Test of Bell’s Inequalities Using Time-Varying Analyzers.” *Physical Review Letters* 49, 1804–1807 (1982). <https://doi.org/10.1103/PhysRevLett.49.1804>
- [4] Hensen, B., et al. “Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres.” *Nature* 526, 682–686 (2015). <https://doi.org/10.1038/nature15759>