Referee Report: Closing objectivity loophole in Bell tests on a public quantum computer

The violation of Bell inequalities stands as one of the most profound discoveries in quantum physics, revealing that correlations arising from entangled states cannot be explained by local realistic theories. However, the persuasiveness of such demonstrations relies on careful scrutiny of the assumptions underlying the measurement process. The manuscript under review focuses on what the authors call the "objectivity loophole": the idea that a measurement outcome should only be regarded as completed when it is objectively recorded, meaning faithfully stored in multiple copies within the apparatus and accessible to external observers.

To address this loophole, the authors rerun Bell tests on IBMQ and IonQ platforms using a modified version of the standard CHSH setup. Starting from a maximally entangled state, each party is equipped with two ancillary qubits. Rather than directly implementing the projective measurements associated with the Bell test, the chosen measurement is decomposed into a unitary operation followed by a computational-basis measurement. In practice, the protocol applies this unitary on the main system, then propagates the outcome information to the ancillary qubits through CNOT gates, and finally performs computational-basis measurements on all qubits. In this picture, the authors simulate three "friends" per party: a measurement outcome of $+1$ or -1 is only assigned if all three agree unanimously, while disagreement leads to assigning the value 0. Using the statistics collected in this way, they compute the CHSH functional and observe violations in some of the tested implementations. In addition, the manuscript also reports an analysis of nonsignalling violations arising in these experiments.

I find the idea of addressing the objectivity loophole interesting, especially from the perspective of "Wigner's friend"-type paradoxes, which probe foundational questions about the nature of measurement in quantum mechanics. However, I found the treatment given in the manuscript less compelling. From a theoretical standpoint, the paper does not appear to present particularly novel insights, and experimentally it essentially consists of sending circuits to publicly available quantum computers—a relatively straightforward task. Additionally, the manuscript is not always easy to read, and the presentation could be clarified in some parts.

My main criticism concerns the choice to implement the objectivity test by creating redundancy of the measurement information quantumly rather than classically. While the redundancy occurs after the unitary representing the measurement, and is therefore related to classical information in principle, encoding it in quantum systems introduces significant drawbacks: the stored information is subject to decoherence, gate errors, crosstalk, and other implementation imperfections. In contrast, a standard Bell test could be performed with a single system per party, and the outcome (which is a classical information) could then be reliably replicated for multiple observers. Such a procedure would be far more robust and less sensitive to the limitations of current quantum hardware. Given these points, I cannot see a clear practical or theoretical advantage in the approach taken by the authors.

While the topic is interesting, in my view the work does not present sufficiently impactful results for a high-impact journal such as *SciPost Physics*. Therefore, I unfortunately cannot recommend this manuscript for publication in *SciPost Physics*. It might, however, be more suitable for a specialized journal in quantum information or quantum computing.

Below, I provide minor suggestions and general comments that may help improve the clarity and focus of the document.

Further Comments

1. In the sentence:

   > "Quantum mechanics is incompatible local realism,vwhich is confirmed by violation of Bell inequalities by two separate parties."

   I believe the word "with" is missing between "incompatible" and "local,".

2. In the sentences:

   > "The communication loophole depends on freedom of choice"

   I think this phrasing could be misleading. The "communication loophole" (also referred to as the "locality loophole") and "freedom of choice" are, a priori, independent loopholes. Presenting them as if one depends on the other may confuse the reader.

3. In the sentence:

   > "In contrast to Bell inequality, it is not allowed both in classical and quantum description"

   I think it would be more clear to say that when experiments are performed respecting space-like separation, nonsignalling is respected both in classical and quantum theory.

4. References [39] and [40] appear to be the same.

5. In equation (4), there appears to be a typo: instead of $\langle A_1 B_1 \rangle_{11}$, I believe it should read $\langle A_1 B_1 \rangle$.

6. I think using the same label for the states in equations (8) and (10) could be a bit confusing.

7. In equation (16), there appears to be a typo: the second term $P(000, 111)$ should likely be $P(111, 000)$.

8. The notation in equation (17) seems somewhat unusual. The operation referred to as "ignoring" resembles what is usually called taking a "marginal" of a probability distribution, which might be a clearer terminology and notation.

9. In the first equation of (18), there appears to be a typo: the expression should be equal to 1/2.

10. In the sentence:

    > "In reality, imperfections make them not zero"

I think this statement could be refined. The reason why these probabilities do not vanish depends on how the experiment is conducted. Indeed, in practice they will never be exactly zero, but if the experiment is performed while closing the locality loophole, the deviation does not stem from imperfections of the setup but rather from the fact that only a finite number of statistics are collected. A genuine violation of nonsignalling under space-like separation would instead imply a breakdown of special relativity.

11. In the ket just below equation (19) there appears to be a typo: it reads " $|-y\rangle$ " but it should read "$|-_y\rangle$".

12. There is a typo in the sentence: "the violation is accompanied by violation of no-signaling in part oth the groups"

13. With respect to the sentence

    > "Due to all-to-all connectivity the test requires only 6 qubits, with two entangled and the friends."

    It is not clear why this would not also be possible with 6 qubits in IBM platforms. As I understand it, the qubit M is used only to isolate the two parties.

14. I found the figures in the appendix a bit disorganized.