# The objectivity of observations in quantum mechanics

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**Abstract:** The objectivity in quantum mechanics is not unambiguous. This issue is illustrated in Wigner's friend thought experiment, where two observers experience different realities according to the deterministic evolution of the Schrödinger equation or according to the collapse when a measurement is performed. This work aims to discuss whether this different observer facts can be described in a framework where both are independent of the observer. To address this question, the problem is exposed and will be discussed.

## I. INTRODUCTION

Wigner's friend thought experiment illustrates one of the thorniest conflicts in quantum theory. It highlights the contrast between the deterministic and continuous nature of processes within isolated systems according to the Schrödinger equation $i\hbar\partial_t|\psi(t)\rangle = \mathcal{H}|\psi(t)\rangle$, as opposed to the probabilistic and discontinuous nature state update after the measurement, where the measurement outcome will be one of the possible eigenvalues with the probability given by $\mathcal{P}(O : \alpha_i) = ||\Pi_i|\psi\rangle||^2$, in which $O$ is a certain observable and $\Pi_i$ is the projector onto the subspace of eigenvalue $\alpha_i$.
In this experiment, a quantum system is subjected to measurements by an observer referred to as Wigner's friend, conducted within a sealed laboratory. Meanwhile, outside the laboratory, another observer, Wigner, remains unaware of the specific measurements carried out by the friend. As previously mentioned, the friend's measurement leads to the assignment of an eigenstate corresponding to the observed outcome, following the state-update rule, while Wigner, assumes the perspective of a super-observer, describing the laboratory and all its contents as a unitary evolving quantum state.
This means that the interpretation of "what is happening inside the laboratory" varies depending on the perspectives of Wigner and Wigner's friend. According to quantum theory, the different descriptions do not lead to an inconsistency, because they have been made by different observers who are in their respective different systems. If the observers do not exchange information about the results, their perceptions of the experiment differ, but when Wigner's friend communicates the result, it is considered as a measurement for Wigner, leading to the collapse of Wigner's state to that of the friend and the system.
The primary question arising from this scenario is whether it exists a theory in which joint probabilities can be assigned to the outcomes of the two observers, assuming the existence of objective properties accessible to both perspectives, known as "facts of the world".

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## II. WIGNER'S FRIEND EXPERIMENT

Once the scenario proposed by Wigner is set out, it is taken the standard description of the experiment, which involves a two-level system, meaning that the system can exist in any quantum superposition of two independent quantum states.
It is considered that the system subjected to measurements is a prepared photon state, existing in a superposition of horizontal $|H\rangle$ and vertical $|V\rangle$ polarizations, described by: $|\phi\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$.
Wigner's friend, who is positioned within the sealed laboratory, measures the polarization using the z-basis: $\{|H\rangle, |V\rangle\}$. Once the measurement is taken, the observer obtains one of the two possible outcomes, which are then recorded in some physical memory as the facts of the friend's measurement, denoted as $|"H"\rangle$ and $|"V"\rangle$.
From Wigner's point of view, he is not exchanging information with the friend, and he can not see the inside of the laboratory, so the initial state is described as a unitary interaction that entangles the photon and the friend's recording. The composite state "polarization + friend's laboratory" described by Wigner is given by:

$$|\Phi\rangle = \frac{1}{\sqrt{2}}(|H\rangle|"H"\rangle + |V\rangle|"V"\rangle), \tag{1}$$

here $|"H"\rangle$ and $|"V"\rangle$ represent orthogonal states.

Wigner can also perform a measurement, but an important remark about the experiment is that he can conduct two types of measurement. He can either exchange information regarding the outcome observed by the friend, causing his own state to collapse accordingly, or he can perform a distinct type of measurement to confirm the presence of superposition. The latter measurement is carried out in the $x$-basis: $|\phi\rangle = \frac{1}{\sqrt{2}}(|H\rangle|"H"\rangle \pm |V\rangle|"V"\rangle)$ and $|\varphi\rangle = \frac{1}{\sqrt{2}}(|H\rangle|"V"\rangle \pm |V\rangle|"H"\rangle)$.

These different descriptions, as mentioned earlier, do not result in inconsistency. However, an alternative version of the experiment is proposed, introducing an exchange of partial information about the results between the two observers.

## III. DEUTSCH'S VERSION OF THE EXPERIMENT

Deutsch [1] proposes a variation of the experiment in which Wigner can acquire direct information of whether a definite outcome of the measurement has been observed by the friend. In Deutsch version, it is imperative that this communication does not contain any information about the observed outcome. Thus, the friend may open the laboratory in a manner that facilitates communication to Wigner while maintaining isolation of all other degrees of freedom.
The information provided will be in the form of: "I have observed a definite outcome" or "I have not observed a definite outcome". The overall state will be:

$$|\Phi\rangle = \frac{1}{\sqrt{2}}(|H\rangle|\text{"}H\text{"}\rangle + |V\rangle|\text{"}V\text{"}\rangle)|\text{"definite"}\rangle. \quad (2)$$

Building upon the universality of quantum theory, even if the message from the friend indicates a definite outcome, Wigner will uphold his assignment of states.
Thus, Wigner not only perceives his own facts but also acquires direct evidence for the existence of the friend's facts. This hints at the coexistence of the two sets of facts, setting out the question: Is it possible to establish a framework where observer-independent facts exist?

In order to address this question, it becomes necessary to introduce a different version of the experiment, an extended one, because we can not acquire the two types of measurement at the same time in order to answer it.

## IV. EXTENDED VERSION OF THE EXPERIMENT

Brukner [2] presents the expanded version of the experiment which involves two super-observers, Alice and Bob, and two observers, Charlie and Debbie. The approach of the experiment is the same, but each pair of observers measure a single photon belonging to an entangled state of two photons (FIG. 1):

$$|\varphi\rangle_{P_1P_2} = \frac{1}{\sqrt{2}}(|\varphi+\rangle_{P_1P_2} + |\varphi-\rangle_{P_1P_2}), \quad (3)$$

where $|\varphi+\rangle_{P_1P_2} = \frac{1}{\sqrt{2}}(|H\rangle_{P_1}|H\rangle_{P_2} + |V\rangle_{P_1}|V\rangle_{P_2})$ and $|\varphi-\rangle_{P_1P_2} = \frac{1}{\sqrt{2}}(|H\rangle_{P_1}|V\rangle_{P_2} - |V\rangle_{P_1}|H\rangle_{P_2})$. Taking that P1 refers to Charlie/Alice's photon and P2 to Debbie/Bob's photon.

Initially the overall state of the polarization for Alice and Bob, including Charlie's and Debbie's laboratories is:

$$|\Phi\rangle_{P_1P_2} = |\varphi\rangle_{P_1P_2}|0\rangle_A|0\rangle_B. \quad (4)$$

Then it is assumed that when Charlie and Debbie perform the measurement of the polarization along the $z$ direction the overall state for Alice and Bob is:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\psi+\rangle + |\psi-\rangle), \quad (5)$$

where

$$|\psi+\rangle = \frac{1}{\sqrt{2}}(|A_H\rangle|B_H\rangle + |A_V\rangle|B_V\rangle), \quad (6)$$

$$|\psi-\rangle = \frac{1}{\sqrt{2}}(|A_H\rangle|B_V\rangle - |A_V\rangle|B_H\rangle), \quad (7)$$

and

$$|A_H\rangle = |H\rangle_{P1}|\text{"}H\text{"}\rangle_C; \ \ |A_V\rangle = |V\rangle_{P1}|\text{"}V\text{"}\rangle_C, \quad (8)$$

$$|B_H\rangle = |H\rangle_{P2}|\text{"}H\text{"}\rangle_D; \ |B_V\rangle = |V\rangle_{P2}|\text{"}V\text{"}\rangle_D. \quad (9)$$

Here as taken previously, states P1 and P2 refers to the photons, while C and D denote the outcomes measured by Charlie and Debbie, respectively.

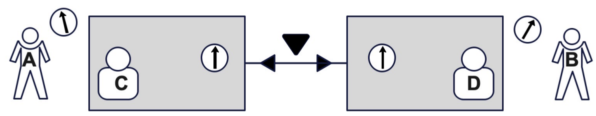


FIG. 1: Wigner's friend experiment of two entangled photon state. Charlie and Debbie, the friends, measure a photon of the pair in the entangled state. Alice and Bob, the super-observers, measure the entire contents of the laboratory; one photon of the pair and the respective friend recording.

Now two sets of binary observables are established, which measure the outcomes along the $z$ and $x$ axis: for Alice observations $A_z = A_0 = |A_H\rangle\langle A_H| - |A_V\rangle\langle A_V|$ and $A_x = A_1 = |A_H\rangle\langle A_V| + |A_V\rangle\langle A_H|$, for Bob observations we can obtain $B_z = B_0$ and $B_x = B_1$ similarly. This is described as such because, as said before, Alice and Bob, can decide which measurement they want to perform, the one performed by the friend's, in the $z$-axis meaning that the laboratory is opened, or Wigner's type of measurement, in the $x$-axis meaning that the superposition is proved.

Brukner [2] uses this extended scenario and considered the following assumptions:

1. Universal validity of quantum theory

2. Locality
3. Freedom of choice
4. Observer-independent facts

where, "Freedom of Choice" implies that Alice and Bob have the control of their measurement choices.

From these four statements, a (no-go) theorem is derived, which asserts that at least one of the assumptions is untrue.
To prove this theorem, it is necessary to observe that statements (2), (3), and (4) necessitate the existence of a joint probability distribution for the four individual facts $P(A_0, A_1, B_0, B_1)$, whose marginals coincide with the probabilities $P(A_i, B_j)$. Any probability distribution satisfying these conditions must adhere to the Bell inequalities, specifically the Clauser-Horne-Shimony-Holt (CHSH) inequality, used for systems with two observables.

If the inequality is violated, at least one of the assumptions is untrue, as stated by Brukner in the (no-go) theorem. So, it is necessary to derive the inequality.

## V. CHSH INEQUALITIES

The CHSH inequality can be derived by considering that the measurement outcomes can only take the values $A_0$, $A_1$, $B_0$, $B_1 = \pm 1$. If all possible combinations are considered, it remains certain that $|A_0B_0 + A_1B_0 + A_0B_1 - A_1B_1| = 2$.
To derive the inequalities, we apply the triangle inequality, $|x + y| \leq |x| + |y|$, and $|E(x)| \leq E(|x|)$, where $E(x)$ represents the expected value of $x$. Relating this expressions:

$$|E(A_0B_0) + E(A_1B_0) + E(A_0B_1) - E(A_1B_1)| \leq 2, \quad (10)$$

where it has been used that $E(|A_0B_0 + A_1B_0 + A_0B_1 - A_1B_1|) = E(2) = 2$ and the expected value defined as: $E(A_iB_j) = \langle A_iB_j\rangle = \sum_{a,b} abP(A_i = a, B_j = b)$.

This represents the CHSH inequality that must be satisfied by any theory implying a joint probability distribution $P(A, B, C, D)$.

It is important to note that in order to test the inequality, the four measurements cannot be taken simultaneously. When one measurement is taken, the system collapses, and the wave function disappears. Therefore, it is not possible to perform all four measurements at the same time. The solution to this challenge is to conduct measurements of identical processes in pairs, in order to determine $P(A_i, B_j)$.

## VI. CHSH TEST

A test assuming the existence of local hidden variables has been carried out, momentarily leaving aside the Brukner assumptions. Assuming only local hidden variables existence, a joint probability distribution must exist, meaning that the condition also adheres to CHSH inequalities.
To verify the inequality in this condition, we have conducted an experiment to measure the individual polarization of two photons. We have been used a laser and a filter in order to make the photon beam monochromatic, and using BBO crystals it has been splitted generating an entangled pair state: $|\phi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_{P1}|H\rangle_{P2} + |V\rangle_{P1}|V\rangle_{P2})$.
Once the two photons are split, their corresponding polarizations can be measured using polarizers. The purpose of these measurements is to determine the four expected values of the inequality, this can be achieved by employing filters and observing whether detection occurred.

If both measured outcomes have the same polarization, the product of the results equals 1. On the other hand, if they are in different polarizations, the product of the results equals -1, leading to the expression: $E(A_iB_j) = (+1)(P_{HH}+P_{VV})+(-1)(P_{HV}+P_{VH})$. These probabilities are calculated according to the coincidences observed in photons passing through the polarizers.
For instance, to determine the value of $P_{HH}$, the filters are both set in the horizontal configuration, and coincidences are recorded within a specific time interval: $P_{HH} = \frac{N_{HH}}{N_{\text{total}}}$. Here, $N_{HH}$ represents the number of coincidences detected by both detectors in the horizontal direction, and $N_{\text{total}}$ denotes the total emitted photons.
Similarly, the other probabilities are obtained by adjusting the filter direction and counting the coincidences again.
Given a constant photon flux and equal measurement time intervals for all four measurements, we have: $N_{\text{total}} = N_{HH} + N_{VV} + N_{HV} + N_{VH}$.
Once these probabilities are determined, the expected value can be computed, as previously defined:

$$E(A_i, B_j) = \frac{N_{HH} + N_{VV} - N_{HV} - N_{VH}}{N_{\text{total}}}. \quad (11)$$

We have considered that the environmental photons detected in the experiment are negligible, as it was conducted in a dark room.

Once the procedure is explained, these expected values are obtained by modifying the direction of the filter, for both the first and second photons.
This implies that in order to acquire four expected values, each containing four probabilities, 16 different measurements must be taken.
Meaning that we need four different vertical axis to

obtain $A_0$, $A_1$, $B_0$ and $B_1$ in the 16 measurements. The angles of the polarizer that define these vertical axes are $\alpha$, $\alpha'$, $\beta$ and $\beta'$, respectively.
However, the selection of these angles is not arbitrary, as the violation of the inequality is dependent on them. According to quantum theory [3], the angles that maximize these expected values are: $\alpha = 0°$, $\alpha' = 45°$, $\beta = 22.5°$, and $\beta' = -22.5°$.

The corresponding setup to obtain $N(\alpha, \beta)_{VV} = N(A_0, B_0)_{VV}$ involves positioning the polarizers at angles $\alpha$ and $\beta$. Following this definition, $N(\alpha, \beta)_{HV}$ is obtained with the polarizers positioned at $\alpha + 90°$ and $\beta$, $N(\alpha, \beta)_{VH}$ with $\alpha$ and $\beta + 90°$, and $N(\alpha, \beta)_{HH}$ with $\alpha + 90°$ and $\beta + 90°$.
The other measurements, $N(\alpha', \beta)_{VV} = N(A_1, B_0)_{VV}$, $N(\alpha, \beta')_{VV} = N(A_0, B_1)_{VV}$, and $N(\alpha', \beta')_{VV} = N(A_1, B_1)_{VV}$, and the related four combinations of directions, are computed following the same procedure as in the previous example.

The method was followed and the different results are shown in the FIG. 2:

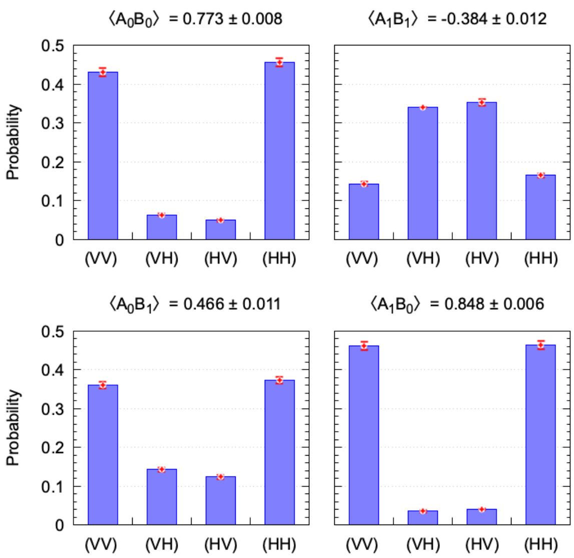


FIG. 2: Experimental data obtained in the CHSH test. It shows the outcome probabilities of the four expected values obtained measuring the coincidences for each case. The red bars indicate the error taken in each probability as a Poison Noise.

The inquality can be computed using this results, yielding $2.473 \pm 0.014$, which indicates a violation of CHSH inequalities.
This violation must demonstrate that there does not exist local hidden variables, and therefore it does not exist a joint probability distribution for the four facts.

Furthermore, it can be observed that the test conducted is analogous to the assumptions made by Brukner, with the only alteration being the replacement of assumption (4) with predeterminism rather than universal independent facts. This Bell test remains indifferent to the specific observables used or the underlying systems, making any violation sufficient to invalidate the conjunction of statements (2), (3), and predetermination.

However, a distinct test is required, the Bell-Wigner test, which relies on highly specific observables to consider assumption (4) as observer-independent facts. These specific observables are defined by any physical system capable of obtaining information from other interacting systems and storing that information in physical memory.

## VII. EXTENDED WIGNER'S VERSION EXPERIMENT TEST

The Bell-Wigner test conducted in [4] aimed to address the issue posed by specific observables in the Wigner's friend scenario. In order to do that it was performed a six-photon experiment, which experimentally violated the associated Bell-type inequality.
In this experiment there were used three photon-pair sources named $S_0$, $S_A$ and $S_B$, which generate pairs of single photons entangled with the following polarization: $|\varphi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B)$, where A and B denote the photons that will be measured by Charlie/Alice and Debbie/Bob respectively.
In the experiment, initially, a pair of photons is created using the source $S_0$, and then the state is rotated in order to maximize the violation of inequalities for this concrete measurement settings. The rotation, $|\tilde{\varphi}\rangle = \mathbb{1} \otimes U_{7\pi/16}|\varphi\rangle$, is achieved using a half-wave plate at an angle of $7\pi/16$, where $U_{7\pi/16} = \cos\left(\frac{7\pi}{8}\right)\sigma_z + \sin\left(\frac{7\pi}{8}\right)\sigma_x$ ( $\mathbb{1}$ is the identity operator, and $\sigma_x$ and $\sigma_y$ are the Pauli operators). The state obtained after this rotation is :

$$\begin{aligned} |\tilde{\varphi}\rangle = & \frac{1}{\sqrt{2}} \cos\frac{\pi}{8}(|H\rangle_A|V\rangle_B + |V\rangle_A|H\rangle_B) \\ & + \frac{1}{\sqrt{2}} \sin\frac{\pi}{8}(|H\rangle_A|H\rangle_B - |V\rangle_A|V\rangle_B). \end{aligned} \quad (12)$$

After the state has been rotated, Charlie and Debbie measure the quantum system described above, recalling the definition of observer provided earlier. To record the measurement results without interfering destructively there were used the other two photon pair sources $S_A$ and $S_B$. Charlie and Debbie measure their photon using Type-I fusion gates, if the photons from $S_0$ and $S_A/S_B$ have different polarization they will exit and will not lead to coincident detection, and if they coincide the information about the outcome is stored, via the ancillary entanglement, in the polarization state of the photon from $S_A$ and $S_B$, acting as a memory, while the single-photon measured $S_0$ is absorbed.
The four-photon state shared by Alice and Bob when

both fusion gates are successful, the global success probability is $\frac{1}{16}$, is:

$$|\tilde{\varphi}'\rangle = \frac{1}{\sqrt{2}}\cos\frac{\pi}{8}(|H\text{"H"}\rangle_A|V\text{"V"}\rangle_B + |V\text{"V"}\rangle_A|H\text{"H"}\rangle_B) + \frac{1}{\sqrt{2}}\sin\frac{\pi}{8}(|H\text{"H"}\rangle_A|H\text{"H"}\rangle_B - |V\text{"V"}\rangle_A|V\text{"V"}\rangle_B). \quad (13)$$

To quantify the inequality, Alice and Bob measure the observables concerning the joint system (photon + record). Once again they can take two different types of measurements, the friend type and the Wigner type. For Alice they are given by:

$$A_0 = \mathbb{1} \otimes (|\text{"}H\text{"}\rangle_A\langle\text{"}H\text{"}|_A - |\text{"}V\text{"}\rangle_A\langle\text{"}V\text{"}|_A), \quad (14)$$

and

$$A_1 = |\phi_+\rangle\langle\phi_+| - |\phi_-\rangle\langle\phi_-|, \quad (15)$$

where $\phi_\pm = \frac{1}{\sqrt{2}}(|H\text{"H"}\rangle_A \pm |V\text{"V"}\rangle_A)$ is the joint system function. They can be defined similar operators $B_0$ and $B_1$ for Bob also.

The procedure in this study was similar to the CHSH test. During the 360 hours they measured the number of photons detected in each of the 64 possible settings. If the photon was detected in both detectors, it was noted as a coincidence. After the measurement period, the probability was calculated as the number of coincidences divided by the total pairs of sent photons.
The average values obtained were: $\langle A_0B_0\rangle = -0.678 \pm 0.033$, $\langle A_0B_1\rangle = 0.570 \pm 0.040$, $\langle A_1B_0\rangle = 0.595 \pm 0.041$, and $\langle A_1B_1\rangle = 0.571 \pm 0.034$. These results yielded a value of $2.416 \pm 0.075$, thereby violating the Bell-Wigner inequality.

The violation of the inequality leads to at least one of the four statements being untrue. Assuming that quantum theory is correct, and that locality and freedom of choice exist, as normally assumed in other fields of physics; therefore, there cannot exist a framework where the two observer realities coexist. Under the assumptions made by Brukner, there is no theoretical framework where one can jointly assign truth values to different observer facts.
A possible solution to this problem is to consider that the "facts of the world" do not exist; instead, facts can only be understood relative to the observer.
It is also possible, but less preferred, that one or more of the other assumptions are not true; for example, the violation of statement (1) in collapse models or statement (3) in super-deterministic theories.

## VIII. CONLUSIONS

This work has examined Wigner's friend thought experiment and the issue of differing observer facts. Once the scenario is set out and different versions of the experiment are presented, the following assumptions are established: Universal validity of quantum theory, Locality, Freedom of choice and Observer-independent facts.
The fulfillment of these assumptions should result in the existence of a joint probability distribution of the facts, and consequently, they must satisfy the CHSH inequality.
The inequalities have been derived, and violation have been demonstrated with an experiment involving specific observables and taking into account the previously mentioned assumptions. This suggests that the assumptions may not hold simultaneously, thereby challenging the classical view of observer-independent reality in quantum mechanics.
Hidden variables necessitate a joint probability distribution and therefore must also adhere to the CHSH inequality. An experiment involving hidden variables, disregarding the above assumptions, has been conducted, and violation have also been demonstrated.

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