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Violation of noninvasive macrorealism by a superconducting qubit: Implementation of a Leggett-Garg test that addresses the clumsiness loophole

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The Leggett-Garg inequality holds for any macrorealistic system that is being measured noninvasively. A violation of the inequality can signal that a system does not conform to our primal intuition about the physical world. Alternatively, a violation can simply indicate that a "clumsy" experimental technique led to invasive measurements. Here, we consider a recent Leggett-Garg test designed to try to rule out the mundane second possibility. We tailor this Leggett-Garg test to the IBM 5Q Quantum Experience system and find compelling evidence that qubit Q_2 of the system cannot be described by noninvasive macrorealism.

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I. INTRODUCTION

The field of quantum computation has stimulated interest in tests of quantum behavior. Such tests have provided standardized protocols to showcase control over qubit systems [1,2]. They can provide metrics for qubit performance. Moreover, as a result of experimental advances associated with the quantum computation era, it has become possible to close loopholes in foundational tests of quantum mechanics [3,4].

While Bell inequality violations [5] retain their canonical status among tests of quantum behavior, they are ill-suited for many experimental systems. To apply a Bell inequality test to a system under investigation, the system must possess two parts that can retain quantum coherence while being segregated until they have a spacelike separation. An alternative to the Bell inequality, one that does not make this demand, is the Leggett-Garg inequality [6,7].

The Leggett-Garg inequality holds for any macrorealistic system that is being measured noninvasively. For completeness, we provide here a brief description of this inequality. We then highlight a "clumsiness loophole" [8] that can hobble its meaningfulness.

Suppose we would like to supply experimental evidence that a system is behaving quantum mechanically. We want this evidence to be convincing to a skeptic who does not initially accept that the system is behaving quantum mechanically. The evidence should attest to some behavior that quantum-mechanical systems exhibit but nonquantum systems do not exhibit. Leggett and Garg suggested that we focus on the following property of quantum systems: generically, they change their state when measured. In other words, generically, measurements on quantum-mechanical systems are "invasive." In contrast, macrorealistic systems are systems that need not change their state when measured (see Ref. [6] for their precise definition of macrorealism). Leggett and Garg derived an inequality that is violated when a measurement changes the state of the system.

Suppose that we go ahead and experimentally demonstrate a violation of the Leggett-Garg inequality for our system of interest. We declare victory and present this violation to our skeptic, certain that the skeptic will now agree that the system is quantum mechanical. To our chagrin, the skeptic is unimpressed. The skeptic agrees that the measurement changed the state of the system—that the measurement was invasive. But the skeptic believes that the change happened not because the system is quantum mechanical, but instead because we did a clumsy job of performing our measurement. The skeptic retorts, "If you measure the position of a cat by throwing a ball at the cat, of course the state of the cat will change. That does not mean the cat is quantum mechanical. Macrorealistic systems *need* not change their state when measured, but of course it is *possible* to change their state with a clumsy measurement." This is the clumsiness loophole. It is essential to address the clumsiness loophole if one wishes to draw meaningful conclusions from a Leggett-Garg test.

The Leggett-Garg protocol has recently been applied to a number of systems with various protocols [9–26]. Some of these efforts have attempted to address the clumsiness loophole, and some have not. We are unaware of any experimental implementation to date of the program designed in Ref. [8], a program that attempts to address the clumsiness loophole in a manner that seems particularly vigilant to us. This program forces the skeptic to conclude that the system is either (i) nonmacrorealistic or (ii) macrorealistic but with the property that measurements collude nonlinearly to disturb the system. In this paper, we implement the Leggett-Garg program designed in Ref. [8] with the IBM 5Q Quantum Experience system [27].

The IBM 5Q Quantum Experience is a publicly accessible system of five superconducting qubits that can be controlled via a website interface. Earlier papers have exhibited the capabilities of the IBM 5Q [28–30]. Our aim is to execute a particularly careful and persuasive demonstration that at least one of the qubits of the IBM 5Q is genuinely quantum, or at least not macrorealistic. Our Leggett-Garg test, which is structured to address the clumsiness loophole in the deliberate manner formulated in Ref. [8], can also productively inform the design of future Leggett-Garg tests of other systems.

The paper is organized as follows: Section II frames the six experimental protocols that make up our Leggett-Garg test. These protocols must be tailored to accommodate constraints in the IBM 5Q system. Section III describes details. Results are supplied in Sec. IV, and we conclude in Sec. V.

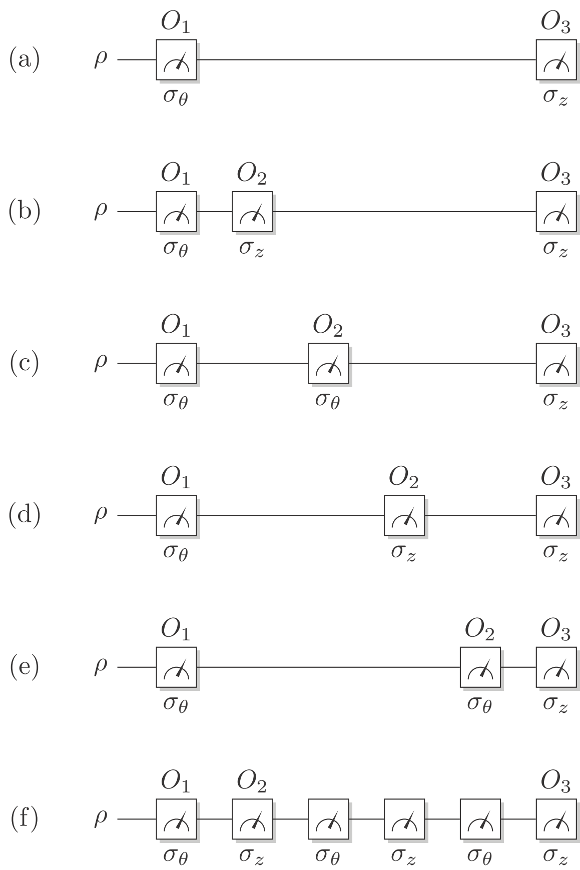

FIG. 1. Proposed Leggett-Garg experimental program. The symbols σ_z and σ_θ should be ignored while deriving the Leggett-Garg inequality, which does not presume any quantum mechanics. The symbol σ_z below, say, O_3 indicates that, in quantum theory, O_3 consists of a measurement along the qubit initialization direction $\hat{z}$. The symbol σ_θ below, say, O_1 indicates that O_1 consists of manipulations and a measurement that are equivalent to a measurement along a direction $\sin\theta\,\hat{y} + \cos\theta\,\hat{z}$ oriented at an angle θ with respect to $\hat{z}$.

II. PROTOCOLS

We seek to test the Leggett-Garg inequality while addressing the clumsiness loophole. This is a subtle task. We would like to frame experiments that can attest to the fact that our measurements are adroit rather than clumsy. But, assuming the system under study is actually quantum mechanical, will not our measurements always disturb the system in a fashion that a skeptic could attribute to clumsiness?

The key is to use the following fact about quantum mechanics: repeated measurements in the *same basis* need not disturb the system. Thus, our experimental program includes preliminary experiments comprised of repeated measurements in the same basis to verify that our measurements are adroit. We then produce a violation of the Leggett-Garg inequality by using only the previously verified measurements.

To see how this works in detail, consider an experimental program comprised of the six protocols depicted in Fig. 1. Focus initially on the first and last protocols, (a) and (f), appearing in the figure.

Protocol (a) shows a physical system measured by some operation O_1 that is arranged to yield a dichotomous result 1 or -1. This system is then subjected to operation O_3 that yields another dichotomous result 1 or -1. One can compute the correlator $\langle O_1 O_3\rangle_a$ by repeating protocol (a) many times and taking the average value of the product $O_1 O_3$.

Protocol (f) shows an interleaved series of manipulations and measurements of the two kinds appearing in protocol (a). In particular, operation O_2 is a manipulation and measurement equivalent to O_3 but occurring earlier in the series. A single run of protocol (f) yields measurement results ± 1 for operations O_1, O_2, and O_3. One can compute the correlators $\langle O_1 O_3\rangle_f$, $\langle O_1 O_2\rangle_f$, and $\langle O_2 O_3\rangle_f$ by repeatedly executing protocol (f), taking the products $O_1 O_3$, $O_1 O_2$, and $O_2 O_3$ each run and averaging over runs.

For any given run of protocol (f), all eight possible values of the triplet $(O_1, O_2, O_3) = (\pm 1, \pm 1, \pm 1)$ satisfy the inequality $O_1 O_3 + O_1 O_2 + O_2 O_3 + 1 \geqslant 0$. Taking the average of this inequality over repeated runs yields an inequality on correlators $\langle O_1 O_3\rangle_f + \langle O_1 O_2\rangle_f + \langle O_2 O_3\rangle_f + 1 \geqslant 0$.

Suppose that our physical system is macrorealistic and that all of the operations in protocol (f) measure it noninvasively. Then,

$$\langle O_1 O_3\rangle_f = \langle O_1 O_3\rangle_a \tag{1}$$

since O_2 and the other operations before O_3 in protocol (f) do not perturb the system. Substituting this into our correlator inequality, we obtain the Leggett-Garg inequality:

$$\mathcal{L} = \langle O_1 O_3\rangle_a + \langle O_1 O_2\rangle_f + \langle O_2 O_3\rangle_f + 1 \geqslant 0. \tag{2}$$

If a system violates this inequality, it is not a macrorealistic system undergoing a noninvasive measurement. One exciting possibility is that the system is impossible to describe correctly by using any macrorealistic noninvasive theory. For instance, perhaps the system is quantum mechanical, exhibiting the strange properties described by quantum theory. But there is a mundane possibility as well. Perhaps the system is macrorealistic and can be measured noninvasively, but our measurements are invasive simply because of our experimental clumsiness. This entirely plausible circumstance is termed the clumsiness loophole in Ref. [8].

To address the clumsiness loophole, our full experimental program includes verification protocols (b)–(e) in Fig. 1 in addition to protocols (a) and (f). These experiments employ repeated measurements of a given kind (i.e., in quantum-mechanical terms, repeated measurements in the same basis). Each protocol (b)–(e) is designed to place a limit, called the ϵ *adroitness*, on the invasiveness of an operation. For the O_2 measurement in the middle of the experiment in protocol (b), for example, we say that it is ϵ_b *adroit* if

$$|\langle O_1 O_3\rangle_b - \langle O_1 O_3\rangle_a| \leqslant \epsilon_b. \tag{3}$$

Similarly, the O_2 measurement in protocol (c) is said to be ϵ_c *adroit* if

$$|\langle O_1 O_3\rangle_c - \langle O_1 O_3\rangle_a| \leqslant \epsilon_c. \tag{4}$$

We define ϵ_d and ϵ_e analogously based on protocols (d) and (e). Assuming that several of these measurements together cannot somehow collude nonlinearly to have an unexpectedly dramatic effect on the system, the maximum effect that the four intermediate measurements in part (f) could have on the

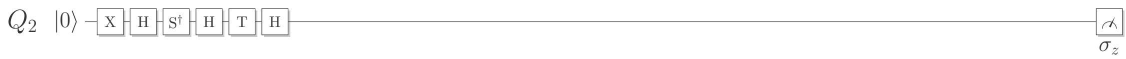

FIG. 2. Protocol (a) of the experiment implemented in a circuit acting on qubit Q_2.

correlation function $\langle O_1 O_3\rangle_f$ is

$$\epsilon_{\text{total}} = \epsilon_b + \epsilon_c + \epsilon_d + \epsilon_e. \tag{5}$$

By separately testing every single operation that appears in Fig. 1 protocol (f), we have direct experimental evidence that none of these operations is causing a mundane violation of the Leggett-Garg inequality (2) by clumsy invasiveness. Designing a Leggett-Garg program with this feature is subtle.

If an experiment yields a value for $\mathcal{L}$ satisfying both

$$\mathcal{L} < 0 \quad \text{and } |\mathcal{L}| \geqslant \epsilon_{\text{total}}, \tag{6}$$

we have evidence that the system can never be correctly characterized by any macrorealistic noninvasive theory.

Suppose that we believe that our system is a qubit correctly described by quantum mechanics. Will it actually exhibit a violation of Eq. (2)? We can derive a quantum-mechanical expression for $\mathcal{L}$ in this set of experiments by using the formulas below, where $\sigma_\theta = \sin\theta\sigma_y + \cos\theta\sigma_z$ and the superoperators $\bar{\Delta}$ and $\bar{\Delta}_\theta$, are defined as $\bar{\Delta}(\rho) = \frac{1}{2}(\rho + \sigma_z\rho\sigma_z)$ and $\bar{\Delta}_\theta(\rho) = \frac{1}{2}(\rho + \sigma_\theta\rho\sigma_\theta)$:

$$\begin{aligned}\langle O_1 O_3\rangle_a &= \tfrac{1}{2}\mathrm{Tr}[\sigma_z,\{\sigma_\theta,\rho\}],\\ \langle O_1 O_2\rangle_f &= \tfrac{1}{2}\mathrm{Tr}[\sigma_z,\{\sigma_\theta,\rho\}],\\ \langle O_2 O_3\rangle_f &= \tfrac{1}{2}\mathrm{Tr}[\sigma_z(\bar{\Delta}_\theta\circ\bar{\Delta}\circ\bar{\Delta}_\theta)(\{\sigma_z,\bar{\Delta}_\theta(\rho)\})].\end{aligned} \tag{7}$$

These formulas imply

$$\mathcal{L} = 2\cos\theta + \cos^4\theta + 1. \tag{8}$$

This value is negative if we choose θ between 0.683π and π or between -0.683π and $-\pi$. We therefore do expect to be able to see a violation of our Leggett–Garg inequality for a qubit. Note also that protocols (b)–(e) were designed with a qubit in mind such that the intermediate measurements should not change $\langle O_1 O_3\rangle$, and the ϵ-*adroitness* parameters should be small. We now tailor this experimental protocol so that it can be implemented on the IBM 5Q.

III. EXPERIMENT

The IBM 5Q consists of five superconducting transmon qubits patterned on a silicon substrate. The qubits are labeled Q_0, Q_1, Q_2, Q_3, and Q_4. There are several constraints on the current qubit setup that are relevant to our proposed experimental program.

First, the IBM 5Q permits only one measurement on a given qubit each experimental run. Figure 1 involves multiple measurements on a single qubit. Rather than performing an additional measurement directly on a single qubit, we therefore perform the measurement by transmitting the qubit's state to an ancilla qubit using controlled-NOT (CNOT) gates and measuring the ancilla qubit. This is just an alternate realization of the measurement operations in Fig. 1; it does not invalidate our carefully constructed Leggett-Garg test.

This modification does force us to consider a second constraint on the IBM 5Q system. For a five-qubit system, one might imagine $5 \times 4 = 20$ different types of CNOT gates, targeting any one of the five qubits and controlled by any of the remaining four qubits. For the IBM 5Q system, only four different types of CNOT gates are available: every CNOT must have Q_2 as the target qubit and Q_0, Q_1, Q_3, or Q_4 as the control qubit. To reduce the number of CNOT gates necessary for our experimental program, we choose Q_2 to play the role of the qubit that appears in Fig. 1 and the other qubits as the internal degrees-of-freedom of the measurement devices in Fig. 1.

The third and final constraint we consider arises from the fact that there are only five qubits in the IBM 5Q. Since each qubit can be measured at most once, any IBM 5Q circuit can only make five total measurements. Protocol (f) of Fig. 1 involves six measurements. To deal with this issue, we erase O_1 from Fig. 1. We change the initial state ρ on

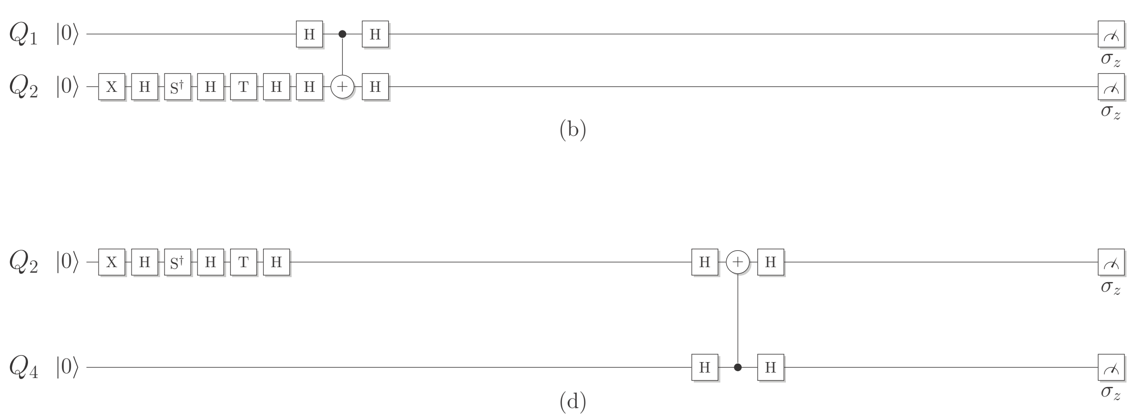

FIG. 3. Protocols (b) and (d) of the experimental program implemented in circuits.

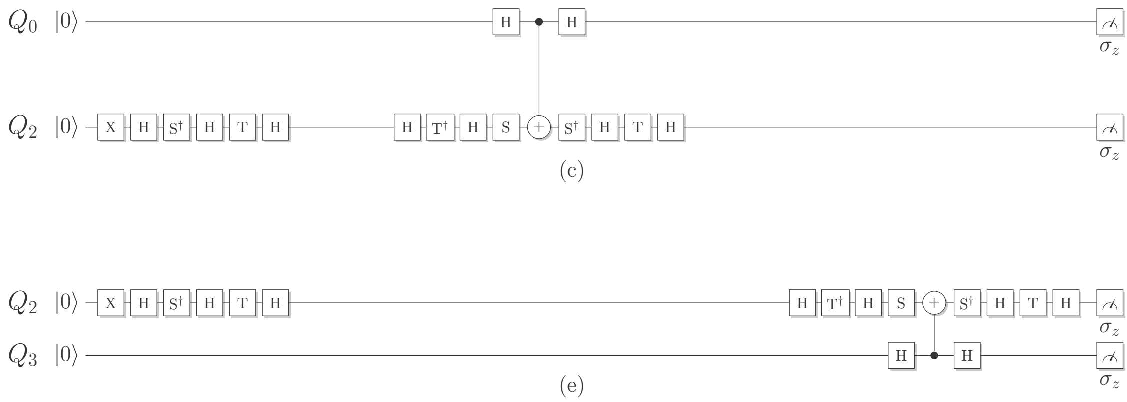

FIG. 4. Protocols (c) and (e) of the experiment program implemented in circuits.

every line of Fig. 1 into $\rho_\theta = |1\rangle_\theta\langle 1|_\theta$, a state that should give result $+1$ when subjected to the O_2 measurement in protocols (c) or (e). With O_1 erased, the protocol (f) correlators satisfy the inequality $\langle O_3\rangle_f + \langle O_2\rangle_f + \langle O_2O_3\rangle_f + 1 \geqslant 0$. The noninvasiveness condition becomes

$$\langle O_3\rangle_f = \langle O_3\rangle_a, \tag{9}$$

and the Leggett-Garg inequality becomes

$$\mathcal{L} = \langle O_3\rangle_a + \langle O_2\rangle_f + \langle O_2O_3\rangle_f + 1 \geqslant 0. \tag{10}$$

For the O_2 measurement in the middle of the experiment in protocol (b), we say that it is ϵ_b *adroit* if

$$|\langle O_3\rangle_b - \langle O_3\rangle_a| \leqslant \epsilon_b; \tag{11}$$

ϵ_c, ϵ_d, ϵ_e are redefined analogously. The Leggett-Garg conditions (6) and the quantum-mechanical predictions (8) are unchanged by this alteration in our experimental program.

To implement the program, it turns out to be convenient to choose $\theta = -3\pi/4$ for our θ measurements in Fig. 1. The IBM 5Q currently permits single qubit gates X, Z, Y, H, S, $S^\dagger$, T, $T^\dagger$ and measurement in the z direction. To perform a $\theta = -3\pi/4$ measurement, we thus rotate the basis noting that the rotation matrix for $\theta = -3\pi/4$ obeys the identity

$$e^{-i3\pi\sigma_x/8} = He^{-i3\pi\sigma_z/8}H. \tag{12}$$

This product has the form $e^{-3i\pi/8}HT^3H = e^{-3i\pi/8}HTSH$. It turns out that the IBM 5Q system exhibits better performance on our experimental program if we reexpress the product as $e^{-i\pi/8}HTHS^\dagger HS^\dagger$ by using the identity $e^{i\pi/4}(HS^\dagger)^2 = SH$. Up to an overall phase, we arrive at the rotation gate

$$R = HTHS^\dagger H. \tag{13}$$

We were permitted to remove the $S^\dagger$ gate on the right end because this matrix R still rotates the eigenstates of σ_z into the eigenstates of σ_θ—the resulting eigenstates of σ_θ just have different overall phases when the $S^\dagger$ on the right end is removed. This is clear from the equations $\sigma_\theta = RS^\dagger\sigma_z SR^\dagger = R\sigma_z R^\dagger$.

We note that a measurement in the θ direction when our qubit is in state $|\psi\rangle$ is given by

$$\begin{aligned}\langle O_\theta\rangle &= |_\theta\langle 1|\psi\rangle|^2 - |_\theta\langle 0|\psi\rangle|^2\\ &= |_z\langle 1|R^\dagger|\psi\rangle|^2 - |_z\langle 0|R^\dagger|\psi\rangle|^2.\end{aligned} \tag{14}$$

Thus, to take a θ measurement, we simply apply $R^\dagger$ to our state, make a z measurement, and then apply R to the result.

Now that we have tailored Fig. 1 to the IBM 5Q, we can run the Leggett-Garg test. Figure 2 gives the circuit for protocol (a). The circuit initializes the system by beginning with an X gate that flips state $|0\rangle_z$ to state $|1\rangle_z$ and the set of gates R that rotates the state to $|1\rangle_\theta$. At the end of protocol (a), the z-directional measurement O_3 is taken.

Moving on to determine ϵ_b from protocol (b) and ϵ_d from protocol (d), we have the two circuits shown in Fig. 3. Note the use of the CNOT gate to record the intermediate state on the second qubit. Because the CNOT gates can only have Q_2 as the target qubit, we must add H gates directly before and after the application of the CNOT gate to both of the qubit states in each experiment. This causes the target qubit and control qubit to exchange roles.

Protocols (c) and (e), shown in Fig. 4, contain intermediate measurements in the θ direction. By combining these with the results from the circuit in Fig. 2, we determine ϵ_c and ϵ_e.

Finally, Fig. 5 gives us the circuit necessary to measure $\langle O_2\rangle_f$ and $\langle O_2O_3\rangle_f$. All five qubits are used and $R^\dagger$ and R

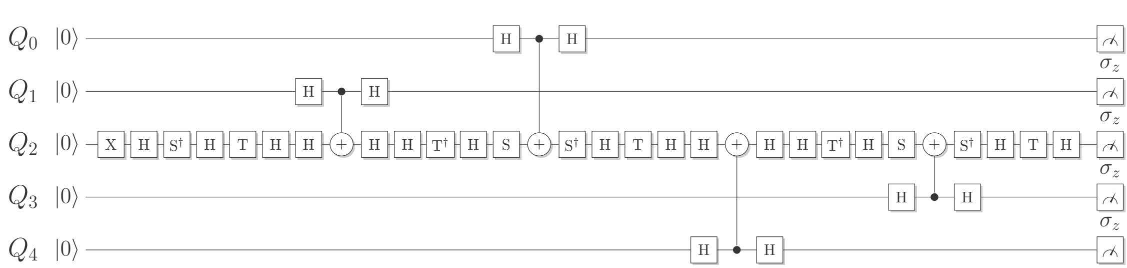

FIG. 5. Protocol (f) of the experiment program implemented in circuits.

TABLE I. The Leggett-Garg result with adroitness test results. Experimentally measured results show agreement with the predictions of quantum mechanics.

	Leggett-Garg quantity				
	$\langle O_3\rangle_a$	$\langle O_2\rangle_f$	$\langle O_2 O_3\rangle_f$	$\mathcal{L}$	
Measured	-0.70 ± 0.01	-0.69 ± 0.01	0.18 ± 0.02	-0.21 ± 0.03	
Quantum prediction	$-\frac{1}{\sqrt{2}} \approx -0.70$	$-\frac{1}{\sqrt{2}} \approx -0.70$	$\frac{1}{4} = 0.25$	$-\sqrt{2} + \frac{1}{4} + 1 \approx -0.16$	
	Adroitness test results				
	$\langle O_3\rangle_b$	$\langle O_3\rangle_c$	$\langle O_3\rangle_d$	$\langle O_3\rangle_e$	ϵ_{total}
Measured	-0.69 ± 0.02	-0.71 ± 0.02	-0.68 ± 0.01	-0.67 ± 0.02	0.08 ± 0.04
Quantum prediction	$-\frac{1}{\sqrt{2}} \approx -0.70$	$-\frac{1}{\sqrt{2}} \approx -0.70$	$-\frac{1}{\sqrt{2}} \approx -0.70$	$-\frac{1}{\sqrt{2}} \approx -0.70$	0

are applied in an interleaved pattern to alternate measurements back and forth between the θ and z directions. The qubit Q_1 is chosen for the measurement O_2 because it has the longest relaxation time of the five qubits of the IBM 5Q and in our experience gave the most reliable results. [This is one of many specific choices in Figs. 2–5 and in the definition (13) that permitted us to achieve a Leggett-Garg violation. The fidelity of the gates in the IBM 5Q system is currently too low to achieve a violation for generic implementations of Fig. 1.]

While Figs. 2–5 show exactly which gates are placed in the circuit and exactly where they are placed in the circuit, several additional gates are placed in the IBM 5Q interface to prevent the IBM 5Q compiler from changing these circuits during execution. In protocol (b), for example, we have two Hadamard gates in a row, HH. To keep the IBM 5Q from collapsing the two gates into an identity gate, we inserted the operator combination $TT^\dagger$ between the two Hadamard gates [31]. This $TT^\dagger$ combination prevents the compiler from combining HH into an identity gate but does not have any other effect on the circuit execution since T and $T^\dagger$ gates physically correspond to timing delays rather than actual pulses. Whenever an instance of HH is found in a protocol, we actually insert $HTT^\dagger H$ into the IBM 5Q interface.

The reason why we must prevent the IBM 5Q from collapsing HH into an identity gate is that we must retain the structure of Fig. 1 to properly address the clumsiness loophole. Consider, for instance, the final H gate on Q_2 in (b) of Fig. 3. This H does not have a second H gate adjacent to it, so it cannot be collapsed into an identity gate. On the other hand, when this same gate is placed into protocol (f) in Fig. 5, it does have a second H next to it. If the IBM 5Q were to collapse these two H gates in (f), then the operation O_2 that was tested in (b) would not be the same operation O_2 that was employed in (f).

On the other hand, to derive circuits (c) and (e) of Fig. 4, we did collapse some HH pairs to the identity on either side of the CNOT gates. These pairs are internal to operation O_2, and they appear together both in (c) of Fig. 4 and in (f) of Fig. 5. Thus, we can collapse them by hand without compromising the structure of Fig. 1. This allows for a reduced number of gates necessary in the circuits.

Additionally, the IBM 5Q allows use of the ID gate, or identity gate. To ensure that the IBM 5Q compiler applies the second H gate on Q_1 (Q_4) directly after the CNOT gate, we fill the space between the second H gate applied to Q_1 (Q_4) and the z-directional measurement at the end with identity gates. Otherwise, the IBM 5Q compiler would apply the H gate immediately before the final measurements [31]. This technique is used whenever we wish to impose a fixed time interval between a gate operating on a qubit and the final z measurement.

IV. RESULTS

Results are summarized by Table I. We performed ten repetitions of the complete experimental program, all six protocols given by Figs. 2–5. Every time we took a measurement, it was actually the output of r repeated executions of the IBM 5Q hardware, where we set $r = 8192$ in the IBM 5Q interface. The data from the ten repetitions allowed us to compute the averages $\langle O_3\rangle_a$, $\langle O_2\rangle_f$, $\langle O_2O_3\rangle_f$, $\langle O_3\rangle_b$, $\langle O_3\rangle_c$, $\langle O_3\rangle_d$, $\langle O_3\rangle_e$, and their associated standard deviation values.

The Leggett-Garg quantity table presents the three averages $\langle O_3\rangle_a$, $\langle O_2\rangle_f$, and $\langle O_2O_3\rangle_f$ obtained from experiments (a) and (f) and their associated standard deviation values σ_1, σ_2, and σ_3. The three averages are added together to compute $\mathcal{L}$ by using Eq. (10). The error bars of $\mathcal{L}$ are obtained by squaring the three standard deviations and taking the square root of their sum $\sigma_{\mathcal{L}} = (\sigma_1^2 + \sigma_2^2 + \sigma_3^2)^{1/2}$.

The second table, labeled Adroitness test results, gives the four average correlation function measurements from protocols (b)–(e): $\langle O_3\rangle_b$, $\langle O_3\rangle_c$, $\langle O_3\rangle_d$, $\langle O_3\rangle_e$, and their associated standard deviation values. To obtain ϵ_{total}, we compute the adroitness of each measurement using equations such as Eq. (11) and total them according to Eq. (5). The error bars of ϵ_{total} are obtained by following the same procedure used for $\mathcal{L}$: we square the standard deviations of the four quantities appearing in Eq. (5) and take the square root of their sum. For reference, we include the quantum-mechanical prediction for each value in the table.

The data confirm that both of the conditions specified in Eq. (6) are met: the calculated $\mathcal{L}$ is indeed negative and $|\mathcal{L}| \geqslant \epsilon_{\text{total}}$.

V. CONCLUSION

We have carefully framed a Leggett-Garg program that (a) addresses the clumsiness loophole and (b) is suited for execution on the IBM 5Q Quantum Experience. This program demonstrates that qubit Q_2 of IBM 5Q is not a macrorealistic system being measured noninvasively. It also supplies compelling evidence that noninvasiveness in the measurements does not exclusively derive from mundane experimental clumsiness. This suggests that it is impossible to formulate a noninvasive macrorealistic description of Q_2.

Some recent papers have stressed the role of equalities rather than inequalities in testing macrorealism [32,33]. One might consider reframing our Leggett-Garg program in the future by directly checking the equality (1) rather than inserting it into the inequality (2).

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