Journal of High School Science



Testing the collapse-locality loophole in Bell experiments: recorder-scale dependence and a mass–distance scaling prediction

Madannavar T

Submitted: July 17, 2026, Revised: version 1, August 23, 2026, version 2, September 26, 2026, version 3, November 3, 2026
Accepted: November 4, 2026

Abstract
Bell inequality violations establish correlations incompatible with local hidden-variable theories, but their interpretation depends partly on when measurement outcomes become physically definite. This uncertainty underlies the collapse-locality loophole, which remains incompletely tested for spontaneous-collapse models. We examine this loophole by combining Kent's causal quantum theory with the Ghirardi–Rimini–Weber (GRW) collapse model to derive a quantitative prediction for the Clauser–Horne–Shimony–Holt (CHSH) Bell parameter. Assuming independent exponential collapse times and effectively instantaneous outcome-dependent amplification, the combined framework predicts $S(N,L) = 2\sqrt{2}\exp(-N\lambda L/c)$, where N is the number of nucleons displaced into distinguishable recording configurations, λ is the GRW collapse rate, and L is the separation between measurement stations. The combined model predicts that increasing the amount of matter displaced by the recording apparatus could progressively weaken and ultimately eliminate the Bell correlations, even though the entangled particles and their detection remain unchanged. In contrast, standard quantum mechanics predicts that these correlations should remain unaffected by recorder scale. We propose systematically varying recorder scale at multiple station separations to map this transition rather than testing a single configuration. The prediction further implies that experiments with equal products $N_1L_1 = N_2L_2 = N_3L_3$ should yield identical CHSH values, providing an independent test of the model's scaling relationship. The proposed approach extends earlier collapse-locality tests by identifying a measurable response curve and a falsifiable scaling law. Its experimental implementation could constrain causal-collapse theories and clarify the physical conditions under which Bell correlations emerge, without resolving the broader interpretive question of quantum non-separability.

Keywords
Quantum entanglement, Bell's theorem, CHSH inequality, Quantum nonlocality, Quantum non-separability, Collapse-locality loophole, Objective collapse models, Ghirardi–Rimini–Weber (GRW) theory, Causal quantum theory, Loophole-free Bell experiments

Trisha Madannavar, Miramonte High School, 750 Moraga Way, Orinda, CA 94563, USA.
trisha.madannavar@gmail.com

https://doi.org/10.64336/001c.175818

1. Introduction

Although quantum entanglement underpins quantum teleportation, cryptography, and computation (1), its physical interpretation remains debated. When Alice measures one particle of an entangled singlet pair, she can predict with certainty the outcome of Bob's measurement along the same axis. However, she cannot use this correlation to transmit information to Bob, because his local measurement outcomes remain random and independent of Alice's measurement choice.

Einstein proposed a criterion of physical reality: if a quantity can be predicted with certainty without disturbing the system, that quantity must be real (2). Alice may choose either property to measure on her own particle, and either choice predicts the matching property of Bob's with certainty, so both properties would appear to be real. Quantum mechanics forbids this, since two non-commuting observables, such as position and momentum, cannot hold definite values at once. This is the Einstein–Podolsky–Rosen (EPR) paradox: the outcomes are always perfectly anti-correlated, as though predetermined, even though quantum mechanics denies that the values can all be definite at once.

Bell's theorem (3) shows, through algebra alone, that any local theory founded on pre-set (hidden-variable) values must obey a strict correlation limit, and that the cosine-law prediction of quantum mechanics exceeds it. Clauser–Horne–Shimony–Holt (CHSH) (4) recast this limit as the noise-tolerant bound $S \leq 2$. Experiments consistently find $S > 2$, a result no local hidden-variable theory can reproduce under the experiments' stated assumptions, as confirmed by the tests of Aspect, Dalibard, and Roger (5), Hensen (6), Shalm (7), and Giustina (8).

Section 3 examines the three candidate explanations in depth: communication between qubits, hidden (pre-set) instructions, or a single system rather than two distinct entities. It defines entanglement, addresses no-signaling, the EPR argument, and the Bell and CHSH inequalities, and then turns to the experimental tests and their loopholes. Section 4 presents our discussion and a proposed experiment on the remaining loophole, and Section 5 our conclusions.

Existing treatments establish that entanglement is non-signaling and violates Bell-type inequalities. They seldom ask whether the surviving picture, a single non-separable system, is empirically distinguishable from non-locality, or how the remaining collapse-locality loophole might be tested. Our contribution is threefold: we argue for the single-system interpretation, examine its limits, and propose an experimental strategy that maps the predicted recorder-scale response of the Bell parameter and tests its scaling with distance.

2. Methods

Papers were identified with search terms including "quantum entanglement," "Bell's theorem," "CHSH," "no-signaling," "EPR," and "loophole-free Bell test" on arXiv and Google Scholar. Articles were included if they were foundational to the field (EPR, Bell,

CHSH), landmark experiments (such as the test of Aspect, Dalibard, and Roger and the 2015 experiments of Hensen, Shalm, and Giustina), or recent interpretive works. Among these, peer-reviewed papers with high citation counts were prioritized. For each source, we examined its central claim, key assumptions, relevance to the three interpretations, and whether it was experimental or theoretical. We then synthesized the material around the three interpretations and assessed how the evidence supported or excluded each. All works were peer-reviewed, cited, and, where possible, independently reproduced, as with the 2015 experiments.

3. Results

3.1 *What entanglement is*

A qubit is a quantum bit, represented mathematically as $|\psi\rangle = a|0\rangle + b|1\rangle$, (eq1), where the squared magnitudes $|a|^2$ and $|b|^2$ give the probabilities of measuring 0 and 1, respectively. A normalized qubit is a quantum state vector whose squared amplitudes sum to unity. Two qubits span four basis states ($|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$), and the general state is written as $|\Psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$, (eq2). To determine whether a pure state is entangled, we compare the product of the "outer" coefficients with that of the "inner" coefficients: $\alpha\delta = \beta\gamma$ (eq3). If the two are equal, the state is separable; if not, it is entangled. For the singlet state ($\alpha = 0$, $\beta = 1/\sqrt{2}$, $\gamma = -1/\sqrt{2}$, $\delta = 0$), $\alpha\delta = 0$ while $\beta\gamma = -½$, so the two are unequal and the state is entangled. Separable qubits each have their own state. Entangled qubits do not: the state describes only the pair as a whole (1).

3.2 *Why entanglement is not communication (no-signaling)*

If Alice's measurement genuinely determined Bob's, she could signal faster than light, which is impossible. Instead, whatever Alice does, Bob's outcomes remain equally likely (50/50). To express this formally, we trace out Alice's subsystem, obtaining the equation $\rho_{Bob} = ½|0\rangle\langle 0| + ½|1\rangle\langle 1| = ½\, I$, (eq4), which shows that Bob's local state is entirely independent of Alice's choice. The situation is analogous to two students in separate rooms completing a true/false answer sheet: each sheet appears to be guessed, yet side by side the answers are always opposite. The correlation lives in the relationship between the results, not in either alone, and learning Alice's result still requires an ordinary, sub-light-speed message (1).

3.3 *EPR: the hidden plan*

The EPR argument of 1935 holds that a quantity is "real" only if its value can be predicted without disturbing the system. EPR contend that quantum mechanics fails this condition for position and momentum, and is therefore incomplete (2). Bohm's spin formulation (9) assumes perfect anti-correlation (Alice and Bob obtain opposite outcomes on every trial), locality (neither can influence the other faster than light), and realism (their outcomes are predetermined). Because Alice measures one axis of Bob's spin without disturbing it, and could equally have measured another, EPR infer that both values were real all along.

3.4 *Bell and CHSH*

Bell's theorem (3), introduced in 1964, showed that the hidden-variable approach yields a testable prediction at odds with quantum mechanics. CHSH (4), in 1969, cast this in its simplest testable form. Alice selects a setting, a or a′, producing an outcome A or A′ (±1), while Bob selects b or b′, producing B or B′ (±1) (Figure 1). The quantity S tests whether a hidden-variable theory can reproduce their correlations, and is defined as

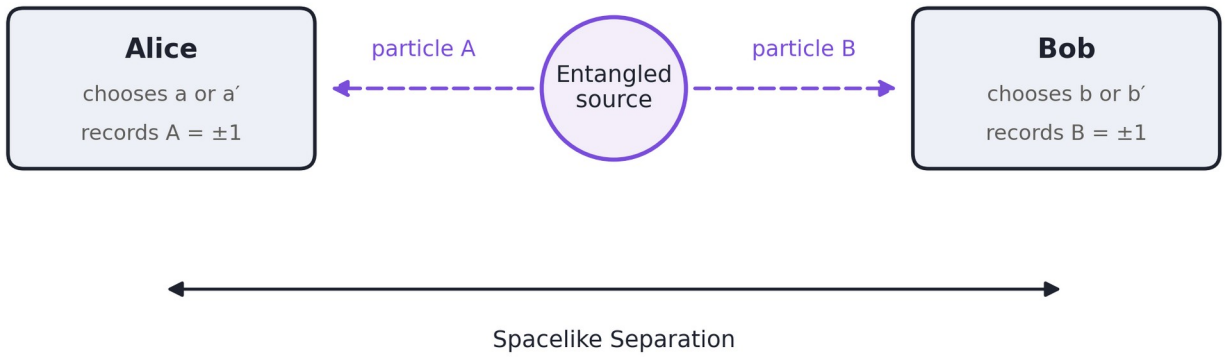

Figure 1. CHSH experimental setup. An entangled source sends one particle to Alice and one to Bob, who are space-like separated so that no light-speed signal can pass between them during a measurement. Alice chooses measurement setting a or a′ and records outcome A = ±1; Bob independently chooses b or b′ and records B = ±1. The four setting combinations are used to compute the CHSH value S.

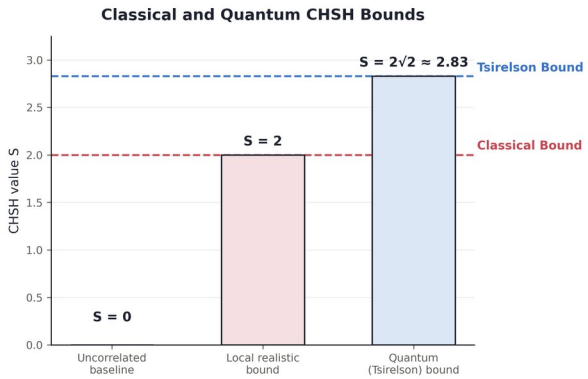

Figure 2. Classical and quantum CHSH bounds. The CHSH value S for three cases: an uncorrelated baseline (S = 0), the local realistic bound (S = 2, the classical bound), and the quantum singlet-state prediction (S = 2√2 ≈ 2.83, the Tsirelson bound). Quantum mechanics exceeds the classical bound of 2.

$S = E(a, b) + E(a, b') + E(a', b) - E(a', b')$, (eq5). If each particle carried fixed, pre-set values for every possible measurement, as the hidden-variable assumption requires, then S could be factored as given by the equation $S = A(B + B') + A'(B - B')$, (eq6). Since B and B′ are each ±1, one bracketed term is always 0 and the other always ±2, so S = ±2 on every trial, whatever the hidden values. This yields the classical bound: $|S| \leq 2$, (eq7). Quantum mechanics instead predicts a cosine-law correlation: $E(a, b) = -\cos\theta$, (eq8),

where θ is the angle between Alice's and Bob's measurement settings. At the optimal angles this gives $S = 2\sqrt{2} \approx 2.83$, (eq9). This value is Tsirelson's bound (10), which exceeds the classical limit of 2 (Figure 2). Bell's original formulation assumed a noiseless experiment. CHSH's noise-tolerant form is the one real experiments use.

3.5 *Experiments and loopholes*

Several experiments have tested Bell's inequality and its noise-tolerant CHSH form. The 1982 experiment of Aspect, Dalibard, and Roger observed a violation of Bell's inequalities at the level of five standard deviations (5). They switched each analyzer's setting while the photons were in flight, so no light-speed signal carrying Alice's setting could reach Bob's analyzer before his measurement finished.

In 2015, experiments by Hensen, Shalm, and Giustina aimed to close the locality and detection loopholes. Hensen entangled electron spins in diamonds separated by 1.3 km and measured $S = 2.42 \pm 0.20$ (6). Shalm, using polarization-entangled photons, found a violation of local realism with $p \approx 5.9 \times 10^{-9}$ (7), an extremely small chance that local hidden variables produced the result. Giustina obtained a comparable violation with $p \leq 3.74 \times 10^{-31}$, using high-efficiency transition-edge detectors, rapid setting changes, and spacelike separation (8).

These experiments nonetheless carry caveats: the loopholes were locality (whether the measurement stations were too close together), detection (whether missed particles biased the sample), and freedom-of-choice (whether external factors influenced the settings). Handsteiner's experiment chose its measurement settings using light from distant stars, showing the correlations could not have been pre-arranged and closing the freedom-of-choice loophole (11). Hensen's experiment, in turn, used photons emitted by each electron spin to herald successful entanglement at a midpoint station. Because only heralded events were counted, undetected electrons never enter the sample and the detection loophole is avoided (6).

One loophole directly relevant to the present proposal remains open: collapse-locality, the question of whether Alice's and Bob's outcomes were truly finalized before comparison. It is a remaining loophole rather than the only logically possible one, but it is the loophole our proposal addresses.

4. Discussion

From these theories and their experimental tests, we conclude that entanglement cannot be used to communicate: neither Alice nor Bob can transmit information through their results (1). This excludes controllable communication, though not every conceivable non-local influence. The 2015 experiments closed the locality and detection loopholes, as described in Section 3, and Handsteiner's starlight settings closed freedom-of-choice (11).

As Catani and Spekkens (12) have argued, such effects are not necessarily unique to quantum theory. Some interference-like and correlation phenomena can also be reproduced by non-quantum models. This raises a central question:

are the correlations of Alice and Bob better explained by non-separability, in which the particles were never genuinely distinct, or by non-locality, in which they remain distinct yet influence one another in a way no local framework allows?

Because no local account reproduces the observed correlations, two readings remain. Alice and Bob may form a single non-separable system, or they may be distinct systems joined by a non-local influence. Current Bell experiments cannot decide between the two, since both produce identical statistics. The choice therefore rests largely on interpretation. The single-system reading is better motivated, by parsimony and no-signaling, since it needs no influence to travel between supposedly separate parts, though it remains unproven. The one place an empirical distinction might yet emerge is the collapse-locality loophole, which we treat as the central open problem below.

4.1 *Previous tests of the collapse-locality loophole*

The collapse-locality loophole, first identified by Kent (13), arises from the interval between a particle's entry into a measurement device and the moment its outcome collapses into a definite value. Every loophole-free Bell test presumes that this collapse occurs at the detector, while Alice and Bob remain space-like separated. Should collapse instead conclude later, the two outcomes may not have been genuinely separated at the instant they became definite, leaving room for a hidden influence.

Three prior works have tested this loophole: an experiment that forced early collapse under a gravitational model (14), a set of proposals for enlarging the space-like window (15), and a timing-based optical test (16). As we describe below, each leaves the Ghirardi–Rimini–Weber (GRW) version of the loophole untested.

Salart et al. (14) performed the first experimental test, in which the detection of a photon at each station triggered a piezoelectric actuator that displaced a 2 mg mirror within approximately 6 μs, with the stations separated by 18 km. Under the gravitationally induced collapse hypotheses of Diósi and Penrose, such a mass displacement collapses in roughly 1 μs, so the collapses at the two stations were space-like separated. The Bell violation persisted, closing the essential loophole for that particular model. The result, however, does not extend to spontaneous-localization models. As Kent later showed (15), the mirror displacement of 12.6 nm falls below the GRW localization length of approximately 100 nm (17), so the two outcome states overlapped, the GRW collapse rate was strongly suppressed, and the resulting collapse time of roughly 2×10^{-4} s exceeded the experiment's 60 μs window. Under GRW, the loophole was never tested.

Kent (15) subsequently proposed stronger tests, principally by enlarging the space-like window itself: placing amplification apparatus at antipodal points on Earth, or in space, so that even slow collapses would complete inside the window. These proposals aim to force an early collapse for a given model. They do not treat the scale of the recording apparatus as a

variable to be swept, and no experiment based on them has yet been performed.

Most recently, Agüero et al. (16) reported an optical Bell test in which classical reference signals and a variable station separation (1 m and 24 m, with all other parameters identical) allowed the detection times of photons to be measured directly. Observing no shift in recorded detection times, they bound the collapse time to below 8.5 ns and conclude that the essential loophole is closed independently of the collapse theory. This conclusion, however, appears to rest on the assumption that collapse manifests as a real delay in the recorded detection time. Under models such as GRW, as emphasized by Kent (15), the detection electronics instead evolve into a superposition of record states, each carrying the same time stamp, and collapse later selects among them without shifting any recorded value. To the extent that this description holds, timing-based bounds do not constrain amplification-dependent collapse models, and the GRW version of the loophole remains open. This is not a criticism of the experiment's internal logic but an observation about the class of collapse models a timing signature can reach. Agüero et al. themselves note that the extended form of the loophole remains untested by their setup.

A gap therefore persists: no experiment has varied the physical scale of the recording apparatus, within a fixed Bell-test geometry, across the regime where the GRW collapse time crosses the space-like window. Each prior test has also operated at a single point: one amplification, one separation, one pass-or-fail outcome. Our proposal targets exactly this gap by mapping the full predicted response instead.

4.2 *A proposed test: sweeping the scale of the recording apparatus*

The two hypotheses differ only when collapse occurs while the stations remain causally disconnected. Standard quantum mechanics predicts $S = 2\sqrt{2}$ regardless of how each outcome is recorded. Kent's causal quantum theory (13), in which collapses are real events that may depend only on their own past light cones, makes two distinct predictions. If one collapse lies in the causal future of the other, the later outcome may depend on the earlier outcome and setting, and the theory reproduces the quantum statistics, $S = 2\sqrt{2}$, through what Kent terms faux non-local correlations (15). If the two collapses are space-like separated, neither has access to the other. Each outcome is drawn independently from its own local state, which for the singlet is an equal mixture of the two results. The experimental question is therefore whether S depends on the scale of the recorder.

We propose a Bell test of fixed geometry, such as Hensen's 1.3 km separation (6) with $T = L/c \approx 4.3$ μs, in which the detection at each station immediately drives a mechanical actuator that displaces a mass, in an outcome-dependent way, by at least the GRW localization length of approximately 100 nm. Throughout, "recorder scale" N means only the number of nucleons placed in distinguishable, outcome-dependent positions by at least this distance. It is not the total mass of the detector or its electronics. This displacement condition, which Salart et al.'s 12.6 nm fell short of (14), ensures the two

outcome states are well separated in the GRW sense, so the recorder collapses at the total rate Nλ, with $\lambda \approx 10^{-16}$ s^{-1} (17). The electron avalanche inside each detector and the electrical signals that precede the actuator displace negligible mass at this scale (15), so the actuator is the first outcome-dependent amplification stage. We assume the displacement is effectively instantaneous. The actuator's finite rise time, the gradual growth of the displacement during it, and the difference between nominal and effectively displaced mass are limitations of the present treatment.

Let tA and tB denote the collapse times of the two records, measured from the simultaneous arrival of the photons. Under GRW these are independent random times with rate Nλ. The two collapse events are space-like separated when neither lies in the other's light cone, that is, when |tA − tB| < T. A shared deadline is not the relevant condition, since a collapse occurring long after the other lies inside its causal future. For independent exponential times, the probability of timelike ordering, |tA − tB| > T, obtained by symmetry as twice the probability that tA exceeds tB by more than T, is $Q(N) = exp(-N\lambda T)$, (eq10).

The two cases contribute differently to the four CHSH correlations. In timelike-ordered runs the later collapse may depend on the earlier outcome and setting, and causal quantum theory reproduces the quantum values, E = −cos θ, for each setting pair. In space-like separated runs the joint probabilities factorize: each station returns ±1 with probability ½ from its local state, independently of the other, so every joint outcome has probability ¼ for every setting combination, giving E = P(+,+) + P(−,−) − P(+,−) − P(−,+) = 0 for each of the four correlations. Such runs therefore contribute S = 0 rather than the Bell bound of 2. Weighting the two cases, whose proportions do not depend on the settings, gives $S(N) = 2\sqrt{2} \cdot exp(-N\lambda T)$, (eq11), whereas standard quantum mechanics predicts S(N) = 2√2 for all N.

Equation (eq11) is an exponential decay in N. Plotted against the logarithm of N, it acquires the apparent sigmoid shape of Figure 3. Two scales must be distinguished: the characteristic collapse scale $N^* = 1/(\lambda T)$, approximately 2×10^{21} nucleons (a few milligrams) for L = 1.3 km, marks where S has fallen to $2\sqrt{2}/e \approx 1.04$. The Bell boundary S = 2 is crossed earlier, at $N = \ln(\sqrt{2})/(\lambda T) \approx 8 \times 10^{20}$ nucleons, roughly 1.3 mg. The prediction is therefore not a decline toward the local bound but a collapse of the correlations themselves, with S falling below 2 and toward 0 as the recorder grows. Because the transition scale varies as 1/T, and hence inversely with station separation, repeating the sweep at several values of L should shift the curve by a predictable factor: doubling L halves the recorder mass at which the decline occurs (Figure 3). This joint dependence on mass and distance is the proposal's principal safeguard, since an instrumental artifact might cause S to decline with actuator mass, but would not reproduce the predicted shift with L. Because the actuator lies downstream of the photon detection, the entangled source, optical channel, and detection chain remain identical at every sweep point, so detection efficiency and channel decoherence are held constant. This

predicted loss of Bell correlations is distinct from the conventional quantum-to-classical transition through decoherence: standard quantum mechanics does not predict that increasing the size of a downstream measurement recorder, while preserving the initial detection process, should systematically reduce the CHSH statistic.

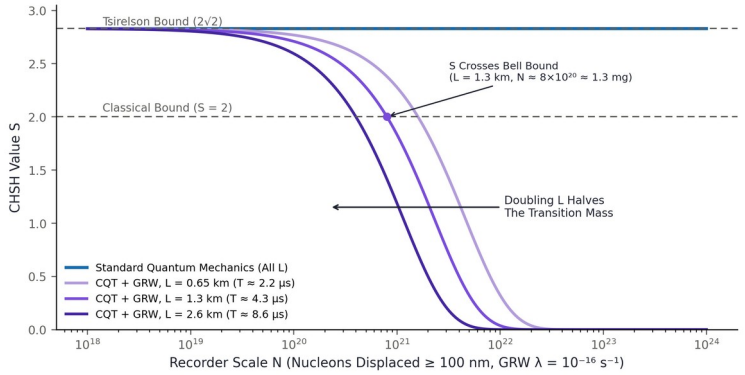

Figure 3. Predicted CHSH statistic S versus recorder scale N under eq11, $S(N) = 2\sqrt{2} \cdot \exp(-N\lambda T)$, for the GRW collapse rate $\lambda = 10^{-16}$ s^{-1} per nucleon. N counts only nucleons displaced, in an outcome-dependent manner, by at least the GRW localization length of approximately 100 nm; it is not the total detector mass. Curves are shown for station separations L = 0.65, 1.3, and 2.6 km, corresponding to space-like windows T = L/c ≈ 2.2, 4.3, and 8.6 μs; standard quantum mechanics predicts the flat line $S = 2\sqrt{2}$ at every scale and distance. For L =1.3 km, the characteristic collapse scale $N^* = 1/(\lambda T) \approx 2 \times 10^{21}$ nucleons (a few milligrams) marks $S = 2\sqrt{2}/e \approx 1.04$, while S crosses the Bell bound of 2 earlier, at $N \approx 8 \times 10^{20}$ nucleons (approximately 1.3 mg). Doubling L halves the recorder mass at which the decline occurs. The apparently sigmoid shape reflects the logarithmic N axis; eq11 itself is an exponential decay.

Previous collapse-locality tests have been endpoint tests: a single recorder configuration and station separation are chosen, and the experiment asks whether collapse occurs early enough for the two events to remain space-like separated. Sweeping the recorder scale asks a different question. By treating the amount of outcome-dependent displaced matter as an experimental variable, the sweep maps the Bell correlations across the predicted transition rather than probing one operating point. Standard quantum mechanics predicts no recorder-scale dependence at all, while the causal-collapse framework predicts the full response of eq11. The novelty of this proposal lies in the mapping strategy, not in eq11 itself, which follows directly from combining GRW with Kent's framework; standard GRW alone, being non-local, would predict no such decay.

Equation (eq11) also contains a scaling prediction. Writing $T = L/c$ gives $S(N, L) = 2\sqrt{2} \cdot \exp(-N\lambda L/c)$, so N and L enter the prediction only through the product NL, and different combinations with the same product predict the same S. The two quantities are not physically equivalent. Increasing N changes the collapse rate $N\lambda$ and hence the distribution of collapse times, while increasing L leaves the collapse dynamics unchanged and

widens the causal interval against which their separation is judged. The model nonetheless predicts that matched changes in these physically distinct quantities produce identical correlations.

This prediction can be tested directly by comparing conditions with $N_1L_1 = N_2L_2 = N_3L_3$. Agreement of S across matched-NL conditions would support the scaling over the tested range. A reproducible difference would show that the simplified relationship is incomplete even if S does depend on recorder scale. Plausible sources of such a departure exist, beginning with the instantaneous-amplification approximation: a real actuator's displacement grows over its rise time, and the displacement relative to the localization length, the spatial distribution of the displaced matter, and the order in which distinguishable configurations develop are all absent from the single parameter N. We do not model these effects and do not assume they break the scaling. They motivate treating the NL scaling as a falsifiable consequence of the simplified model rather than an assumption. The contribution of this proposal is therefore twofold: mapping the recorder-scale response predicted by the causal-collapse framework, and testing whether the NL scaling survives physically distinct implementations.

Though neither outcome would settle what entanglement is, both would be informative. Observation of the decay of eq11, reproducing its predicted dependence on both recorder scale and station separation, would be evidence for an objective, amplification-dependent collapse process constrained by local causality. If S instead remains at $2\sqrt{2}$ across the sweep, the result would not prove non-separability. It would instead rule out causal quantum theory combined with GRW for all collapse rates $\lambda \gtrsim 1/(N_{max} T)$, where N_max is the largest scale tested, a region no previous experiment has constrained.

5. Conclusion

Although no-signaling and Bell's theorem constrain explanations of quantum entanglement, they do not uniquely establish its physical interpretation. In particular, the collapse-locality loophole leaves open the question whether measurement outcomes become definite while the two stations remain causally disconnected. The principal contribution of this study is to turn this unresolved question into an experimental strategy built on a quantitative, falsifiable prediction. By combining Kent's causal quantum theory with the GRW collapse model, we derive $S(N,L) = 2\sqrt{2}\exp(-N\lambda L/c)$, which leads to a striking prediction: increasing the amount of matter displaced by the recording apparatus could progressively weaken and ultimately eliminate the Bell correlations between entangled particles, even without changing the entangled source or the initial detection process. Standard quantum mechanics predicts no such recorder-scale dependence. This difference provides a direct, falsifiable distinction between the two theoretical frameworks.

Rather than testing a single experimental configuration, we propose systematically mapping this response across recorder scales and station separations, thereby identifying the

predicted transition from quantum correlations toward statistically independent outcomes. Crucially, the model also predicts that physically distinct experimental configurations satisfying $N_1L_1 = N_2L_2 = N_3L_3$ should yield identical CHSH values, providing an independent and potentially more discriminating test of the proposed scaling relationship. Observing both the predicted decay and its mass–distance scaling would support the combined causal-collapse framework, whereas their absence would constrain or exclude it over the experimentally accessible parameter range. Thus, the novelty of this work lies not in proposing a new interpretation of entanglement or a new collapse mechanism, but in converting existing theoretical principles into a testable response curve and scaling law that could distinguish competing descriptions of quantum measurement.

Acknowledgments

The author thanks Dr. Damián Pitalúa-García and the Cambridge Centre for International Research (CCIR) for their guidance and mentorship throughout this project. The author used AI for help with understanding, language editing, and figure code, and takes full responsibility for the final content.

6. References

1. Nielsen MA, Chuang IL. Quantum Computation and Quantum Information, 10th Anniversary ed. Cambridge University Press, Cambridge, UK, 2010. https://doi.org/10.1017/CBO9780511976667

2. Einstein A, Podolsky B, Rosen N. Can quantum-mechanical description of physical reality be considered complete? Phys Rev, 47: 777-780, 1935. https://doi.org/10.1103/PhysRev.47.777

3. Bell JS. On the Einstein Podolsky Rosen paradox. Phys Phys Fiz, 1: 195-200, 1964. https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195

4. Clauser JF, Horne MA, Shimony A, Holt RA. Proposed experiment to test local hidden-variable theories. Phys Rev Lett, 23: 880-884, 1969. https://doi.org/10.1103/PhysRevLett.23.880

5. Aspect A, Dalibard J, Roger G. Experimental test of Bell's inequalities using time-varying analyzers. Phys Rev Lett, 49: 1804-1807, 1982. https://doi.org/10.1103/PhysRevLett.49.1804

6. Hensen B, Bernien H, Dréau AE, Reiserer A, Kalb N, Blok MS, 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

7. Shalm LK, Meyer-Scott E, Christensen BG, Bierhorst P, Wayne MA, Stevens MJ, et al. Strong loophole-free test of local realism. Phys Rev Lett, 115: 250402, 2015. https://doi.org/10.1103/PhysRevLett.115.250402

8. Giustina M, Versteegh MAM, Wengerowsky S, Handsteiner J, Hochrainer A, Phelan K, et al. Significant-loophole-free test of Bell's theorem with entangled photons. Phys Rev Lett, 115: 250401, 2015. https://doi.org/10.1103/PhysRevLett.115.250401

9. Bohm D, Aharonov Y. Discussion of experimental proof for the paradox of Einstein, Rosen, and Podolsky. Phys Rev, 108: 1070-1076, 1957. https://doi.org/10.1103/PhysRev.108.1070

10. Cirel'son BS. Quantum generalizations of Bell's inequality. Lett Math Phys, 4: 93-100, 1980. https://doi.org/10.1007/BF00417500

11. Handsteiner J, Friedman AS, Rauch D, Gallicchio J, Liu B, Hosp H, et al. Cosmic Bell test: measurement settings from Milky Way stars. Phys Rev Lett, 118: 060401, 2017. https://doi.org/10.1103/PhysRevLett.118.060401

12. Catani L, Leifer M, Schmid D, Spekkens RW. Why interference phenomena do not capture the essence of quantum theory. Quantum, 7: 1119, 2023. https://doi.org/10.22331/q-2023-09-25-1119

13. Kent A. Causal quantum theory and the collapse locality loophole. Phys Rev A, 72: 012107, 2005. https://doi.org/10.1103/PhysRevA.72.012107

14. Salart D, Baas A, van Houwelingen JAW, Gisin N, Zbinden H. Spacelike separation in a Bell test assuming gravitationally induced collapses. Phys Rev Lett, 100: 220404, 2008. https://doi.org/10.1103/PhysRevLett.100.220404

15. Kent A. Stronger tests of the collapse-locality loophole in Bell experiments. Phys Rev A, 101: 012102, 2020. https://doi.org/10.1103/PhysRevA.101.012102

16. Agüero M, Bourdieu J, Hnilo A, Kovalsky M, Nonaka M. Test of the essential collapse-locality loophole. arXiv:2603.24909, 2026. https://doi.org/10.48550/arXiv.2603.24909

17. Ghirardi GC, Rimini A, Weber T. Unified dynamics for microscopic and macroscopic systems. Phys Rev D, 34: 470-491, 1986. https://doi.org/10.1103/PhysRevD.34.470