QUANTUM PHYSICS

Satellite testing of a gravitationally induced quantum decoherence model

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Quantum mechanics and the general theory of relativity are two pillars of modern physics. However, a coherent unified framework of the two theories remains an open problem. Attempts to quantize general relativity have led to many rival models of quantum gravity, which, however, generally lack experimental foundations. We report a quantum optical experimental test of event formalism of quantum fields, a theory that attempts to present a coherent description of quantum fields in exotic spacetimes containing closed timelike curves and ordinary spacetime. We experimentally test a prediction of the theory with the quantum satellite *Micius* that a pair of time-energy–entangled particles probabilistically decorrelate passing through different regions of the gravitational potential of Earth. Our measurement results are consistent with the standard quantum theory and hence do not support the prediction of event formalism.

Quantum mechanics and the general theory of relativity describe our world from completely separate perspectives. Although highly expected, a coherent interface between quantum theory and the theory of general relativity remains elusive (*1*–*3*). In response to this situation, new ideas have been conceived, particularly from the quantum optical approach, to test fundamentals of the interplay between quantum theory and the gravity theory (*4*–*13*). Among these approaches, event formalism of quantum fields is particularly interesting because it presents a coherent description of quantum fields in exotic spacetimes containing closed timelike curves (CTCs) and ordinary spacetime. The exotic spacetimes are interesting both because they are a fundamental feature of general relativity and because such spacetime structures could be formed owing to quantum fluctuation of spacetime itself—that is, originating at a deeper level from quantum gravity (*14*).

The discussion of quantum mechanics in exotic spacetimes with CTCs that violate causality has attracted attention (*15*–*19*). Although many proposals for solving this problem have been discussed, the approach that follows most directly from standard quantum field theory is the path-integral approach, where coherent, action-weighted sums over all single-valued (i.e., self-consistent) histories are evaluated (*20*, *21*). For exotic spacetimes, a nonstandard renormalization is typically required to preserve the probabilistic interpretation of the theory. Equivalently, this approach corresponds to teleportation models of CTCs (*22*, *23*), where postselection plays the role of the renormalization. However, these models violate a basic tenet of relativity by allowing signaling faster than the speed of light. This happens because the characteristic quantum feature of entanglement allows acausal effects within the compact region containing the CTCs to spread into the surrounding spacetime (*21*, *24*).

An alternative approach that avoids this problem argues that inconsistent evolutions of quantum states in spacetimes with CTCs could be avoided for arbitrary initial conditions by taking the density operator describing the local quantum state as the fundamental object that is required to be self-consistent within the CTC region (*17*). This has the effect that any entanglement between systems traversing the CTC and systems that do not is erased, thus preventing acausal effects from spreading outside. Such a feature could arise in quantum field theory, where it was suggested that this behavior could be understood as a differential decay of the commutator between field modes propagating in different metrics. A speculative new theory was established on the basis of this observation: event formalism (*11*). As a nonlinear extension of ordinary quantum theory, event formalism attempts to present a coherent description of quantum fields for both ordinary spacetime and nonhyperbolic spacetimes containing CTCs (*11*, *12*, *25*). Event formalism makes predictions that can be tested in the gravitational wells of planetary objects.

The mode operator in event formalism is given as (*11*)

$$\hat{a}(t,x) = \int dk g(k) e^{ik(x-t)} \int d\Omega J(\Omega) e^{i\Omega(t_d-\tau)} \hat{a}_{k,\Omega} \tag{1}$$

where $g(k)$ is the photon spectral distribution; for simplicity, we work in $(1+1)$ spacetime coordinates. An extra degree-of-freedom, Ω, is introduced with a distribution of $J(\Omega)$. τ is given as

$$\tau = \int_t^{t_d} ds \tag{2}$$

where ds is the propagation time across an incremental local reference frame, t_d is the photon detection time in asymptotically flat global coordinates, and t can be interpreted as the photon emission time.

It can be shown that in event formalism, the mode operators at different spacetime locations along the photon trajectory commute to be compatible with exotic spacetime-containing CTCs. However, they follow the same commutation relation as standard quantum theory in flat spacetime (*11*, *25*). This new formalism of quantum fields predicts that a pair of time-energy–entangled photons may decohere if they pass through different regions of a curved spacetime. Suppose that a pair of time-energy–entangled photons are generated at a ground station. One photon of the pair is detected at the ground station and its entangled twin is sent to and detected at a satellite orbiting around Earth. Event formalism predicts that in this setting, the initially time-energy–entangled pair of photons probabilistically decorrelate in time, which is different from the predictions of standard quantum theory (*12*, *13*). At the same time, the properties of single photons remain unchanged. For the pairs of photons remaining time-energy entangled, their correlation properties are given by the standard quantum theory; for the pairs of photons decorrelated in time, the observed two-photon coincidence events spread out. Observationally, the decoherence effect predicted by the event formalism will be the sum of these two effects. The probability of losing the time-energy entanglement, P, is characterized by the decorrelation factor, D, with $D = 1 - P$. This can be quantified by the ratio between the two-photon coincidence probability in event formalism and that in standard quantum theory, which is given by $D \approx \exp(-0.5\Delta_t^2/d_t^2)$ (*11*, *13*), where d_t is the photon coherence time and Δ_t comes from the effect of curved spacetime as derived in (*13*, *26*). Event formalism also predicts that in the same setting, the correlation properties of faint coherent laser pulses is completely described by the standard quantum theory. We present an experimental study of these predictions that is based on the

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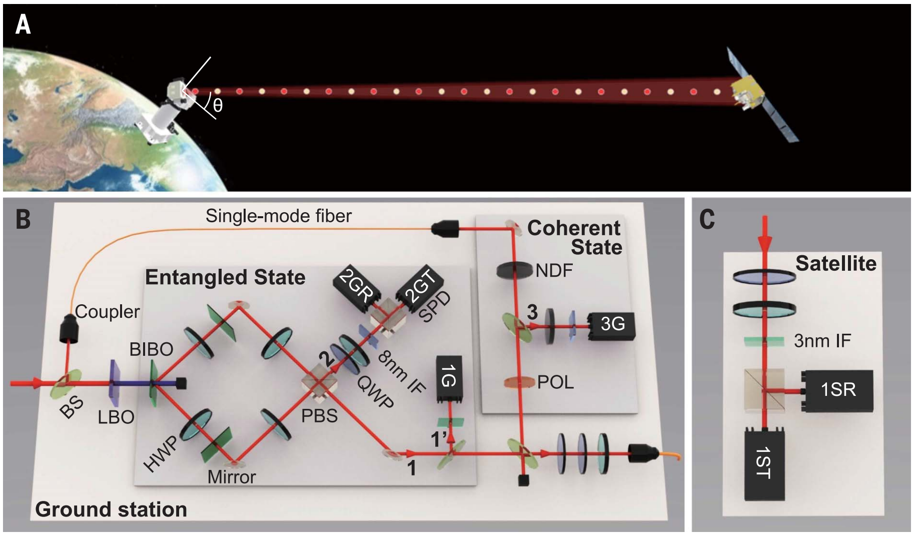

Fig. 1. Schematics of experimental test of event formalism in Earth's gravitational field. (**A**) The ground station sends both entangled single photons and faint coherent laser pulses to the satellite *Micius*. (**B**) Preparation of entangled photon pairs and faint coherent laser pulses at the ground station. Note that all beam splitters (BSs) have a reflectivity of ~2%. We use the reflected laser pulses at 780 nm to prepare faint coherent laser pulses, upconvert the rest in an LiB_3O_5 (LBO) crystal to 390 nm, and then down-convert the 390-nm photons in a 1-mm BiB_3O_6 (BIBO) crystal into polarization-entangled photon pairs (780 nm) (*27*). The pair of photons exit separately into paths 1 and 2. The faint coherent laser pulses and entangled single-photon pulses in path 1 are combined, coupled into a single-mode optical fiber, and directed to the transmitter to be launched to the satellite. (**C**) Single photons received by the satellite are passed through polarization analysis and detected by single-photon detectors (SPDs). SPDs are labeled by 1G, 2GR, 2GT, 3G, 1ST, and 1SR. Refer to (*27*) for high-bandwidth, high-precision stabilization of the ground station-satellite optical link and synchronization. HWP, half-wave plate; QWP, quarter-wave plate; IF, interference (band-pass) filter; PBS, polarizing beam splitter; NDF, neutral density filter; POL, polarizer.

quantum satellite *Micius* (*27*). A feasibility study of such experiments was recently presented (*13*). The basic requirement for the predicted decorrelation effect is that the difference between the locally measured propagation time along the photon trajectory in the gravitational well, τ, and the propagation time as measured by a clock in flat space, t_d, differ by an amount that is significant with respect to the photon pulse length.

Micius was launched recently to a sun-synchronous orbit with an altitude of ~500 km. The end-to-end loss of the free space optical link, from light launched by the transmitter antenna at the ground station to light detection at the satellite, was determined to be <50 dB on average at the wavelengths of interest, which was sufficient for the demonstration of quantum teleportation between ground station and satellite, with fidelity surpassing the classical limit (*27*). This established quantum optical platform offers an excellent opportunity to experimentally examine theoretical proposals on the interplay between quantum theory and gravity, such as event formalism.

The schematics of the experiment are depicted in Fig. 1. The system was originally developed to teleport single-photon quantum states from the ground station at Ngari, Tibet, China (latitude: 32°19′33.07″ N; longitude: 80°1′34.18″ E; and altitude: 5047 m) to *Micius* (*27*). In this work, we generated entangled photon pairs at the ground station and examined the time correlation between one photon at the ground station and its twin distributed to the quantum satellite. We denote the measured two-photon coincidence event as $C_{\text{exp,EPR}}(\theta)$. For comparison, we also recorded two-photon coincidence events $C_{\text{exp,COH}}(\theta)$ with pulsed coherent laser light source in the same setting. Here, θ is the altitude angle of satellite with respect to the ground station. *Micius* orbits Earth by a different pass in each night. For different passes, it takes a different amount of time for the altitude angle of satellite varying from 40° to 60° (data collection range in the experiment, Fig. 2); the numbers of two-photon coincidence events and background events that are functions of θ are pass dependent, i.e., they may vary significantly as the satellite takes different passes. However, the decorrelation factor, $D(\theta)$, is only a function of the altitude angle, θ, i.e., pass independent, in our experimental configuration. To reduce the statistical error in our data analysis, in the experiment associated with one satellite pass, we group the two-photon coincidence events for every 5° ($\Delta\theta = 5°$) of altitude angle as one data point, $C_{\text{exp,EPR}}(\theta)$ and $C_{\text{exp,COH}}(\theta)$, with $40° < \theta < 60°$. For each of these data points, we estimate the number of two-photon coincidence events on the basis of standard quantum theory with $C_{\text{SQT,EPR}}(\theta) = \eta_2 S_{\text{EPR}}(\theta)$, where $S_{\text{EPR}}(\theta)$ is the number of the single-photon detection events that are due to the entangled photon pair source at the satellite and $\eta_2 = 34.4\,(2)\%$ is the efficiency of detecting entangled photons in path 2 (Fig. 1B). The two-photon coincidence events that are due to faint coherent laser pulses are given by $C_{\text{SQT,COH}}(\theta) = S_{\text{COH}}(\theta) S_3 t_p / t_{\Delta\theta}$, where $S_{\text{COH}}(\theta)$ and S_3 are the numbers of single-photon detection events that are due to faint coherent laser pulses at the satellite and

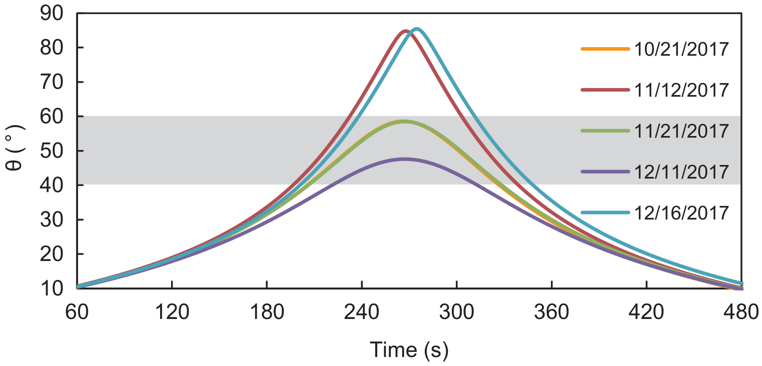

Fig. 2. Satellite passes. The altitude angle (θ) of satellite with respect to its flying time for five different satellite passes labeled by dates (for data in Fig. 4A), where we arbitrarily set the time for the altitude angle of the satellite to be $\theta = 5°$ as the origin of the (horizontal) time axis. We choose to collect experimental data for $\theta \in [40°, 60°]$ (gray-shaded area), in which the photon loss is relatively small, and we have more satellite passes for better statistics. Note that the satellite passes on 10/21/2017 and 11/21/2017 (Beijing time, UTC/GMT +8) happen to be on the opposite sides (west side and east side) and are symmetric with respect to the ground station; the altitude angles of the two passes basically coincide.

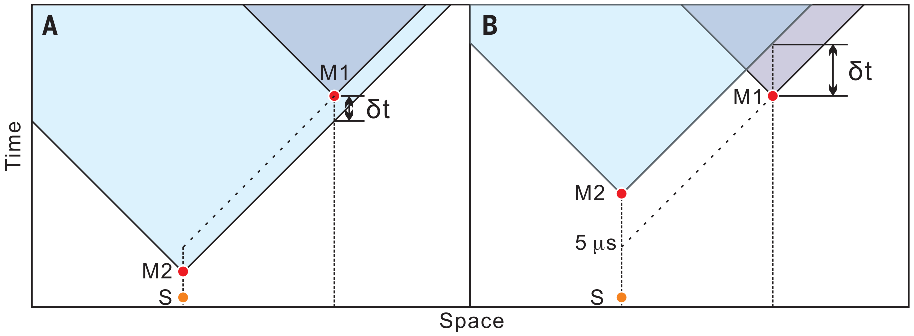

Fig. 3. Spacetime diagram for the detection of a pair of entangled photons in the experiment. A pair of entangled photons are created at the ground station (event S). Whereas one photon is detected at the ground station (event M2), its twin is sent to the satellite, where it is detected (event M1). (**A**) Counting all latency, the wavefront from finishing event M2 arrives earlier than the earliest time of event M1 by δ*t* ~ 18 ns. The two events are not space-like separated (*26*). (**B**) With the insertion of s 1-km fiber in path 2, the wavefront from the earliest time of finishing event M2 arrives later than the latest time of finishing event M1 by δ*t* ~ 5 μs. The two events are space-like separated. The line-of-sight distance between satellite and ground station varies between 550 and 740 km. (Figure is not drawn to scale.)

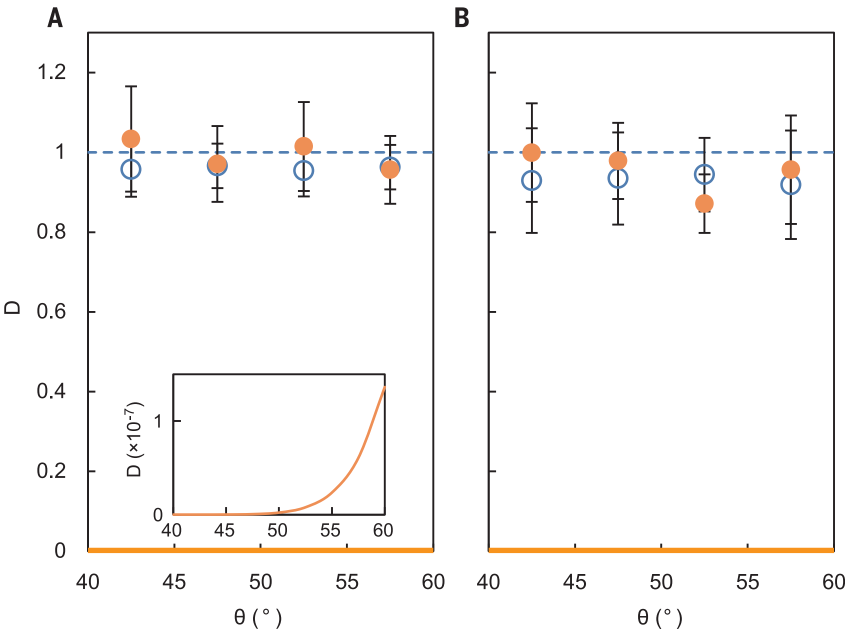

Fig. 4. Experimental estimation of decorrelation factors. Decorrelation factors are plotted as a function of the satellite's altitude angle (θ) for without and with fulfilling the nonsignaling condition in (**A**) averaged over five satellite passes and (**B**) averaged over four satellite passes, respectively. Open circles: experimental results with entangled photon pair source; filled circles: experimental results with coherent laser source; smooth line: predictions of event formalism. Error bars are 1 SD estimated over the relevant numbers of satellite passes. Inset: magnified view of the predictions of event formalism.

in path 3, respectively, t_p = 12.5 ns is the pulse-to-pulse separation (*26*), and $t_{\Delta\theta}$ is the time to collect data for Δθ = 5°. We then obtain the decorrelation factor in the *i*th satellite pass as $D_{\mathrm{EPR}}(\theta,i) = C_{\mathrm{exp,EPR}}(\theta,i)/C_{\mathrm{SQT,EPR}}(\theta,i)$ for the entangled photon pair source and as $D_{\mathrm{COH}}(\theta,i) = C_{\mathrm{exp,COH}}(\theta,i)/C_{\mathrm{SQT,COH}}(\theta,i)$ for the faint coherent laser source, respectively. For a total number of N satellite passes, we obtain the decorrelation factors as $D_{\mathrm{EPR}}(\theta) = \sum_i D_{\mathrm{EPR}}(\theta, i)/N$ and $D_{\mathrm{COH}}(\theta) = \sum_i D_{\mathrm{COH}}(\theta, i)/N$, respectively. Note that we attenuate the coherent laser pulses to make the two-photon coincidence rates similar to that for the entangled photon pair source.

We conducted the experiment with and without fulfilling the no-signaling condition to account for certain quantum collapse models (*28*, *29*). The no-signaling condition is realized by adding a 1-km optical fiber in path 2 at the ground station such that the detection event of a single photon in path 2 is separated space-like from the detection event of its entangled twin at the satellite (Fig. 3) (*26*). The measurement results for both spacetime settings are plotted in Fig. 4, A and B (*26*), respectively. Given our experimental condition with d_t ~ 0.07 mm (≈0.2 ps) (*26*) and satellite altitude of ~500 km, event formalism predicts decorrelation effects, $D(\theta) < 10^{-6}$ for 40° < θ < 60° (smooth lines). In contrast to these predictions, we observe that the experimentally measured decorrelation factors, $D_{\mathrm{EPR}}(\theta)$ (Fig. 4, filled circles) and $D_{\mathrm{COH}}(\theta)$ (Fig. 4, open circles), are flat in the same range of θ and scatter around 1 (standing for no decorrelation) for all conditions in the study, i.e., including entangled photon pair source and faint coherent laser source and with or without satisfying the no-signaling condition. We thus conclude that our experimental results are consistent with the descriptions of standard quantum theory and do not support the predictions of event formalism.

It is a generic feature of many speculative theories attempting to modify quantum mechanics to be more consistent with general relativity in that decoherence of entanglement appears under conditions where standard quantum theory does not predict decoherence. Here, we have tested the specific predictions of event formalism and find they are not supported; however, this does not necessarily rule out other approaches. Indeed, even within event formalism, there is some ambiguity as to the scale of the effect. If, instead of taking the global time, t_d, as defined by a clock in asymptotic flat space (as assumed here and in the original proposal), one uses a clock local to the detector as the global reference, then a weaker decoherence effect is predicted, with $D(\theta)$ between 0.96 and 0.98 for the current experimental configuration. An experimental study of this weaker decoherence effect with sufficient statistical confidence requires a significant number of satellite passes. This is far beyond the lifetime of *Micius* and thus we plan to perform such a test in a future experiment (*26*). Moreover, considering that the two-photon coincidence time window (3 ns) is a few thousand times bigger than the photon coherence time (0.2 ps) in this experiment, future experiments may improve the temporal resolution to the order of the photon coherence time. This will not only present a conclusive experimental verification of these decoherence effects, but will also provide more insightful knowledge about a number of interesting gravity-related models, including event formalism, gravitational dilation, and broadening (*30*, *31*).

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SUPPLEMENTARY MATERIALS

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A test of quantum gravity

Quantum mechanics and the general theory of relativity represent two pillars of modern physics, but unification of the two theories remains an open problem. Theories of quantum gravity abound, but they tend to lack an experimental foundation. One such proposed theory, event formalism, predicts that a pair of entangled particles decorrelate as they pass through different regions of the gravitational well of a planetary object. Xu *et al.* present results of a quantum optical test of this proposal using the quantum satellite Micius. Using entangled photon pairs, one sent to the satellite and the other retained on Earth, they find no evidence for the predicted decorrelation effects. The results may help shed light on the interplay between quantum theory and gravity.

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