Spooky action at a distance also acts in the past

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The term ‘spooky action at a distance’ was coined by A. Einstein to show inconsistency of quantum mechanics with the principle of locality and reality. However, quantum mechanics is nonlocal and violates Bell’s inequality. A quantum state measurement of a particle of an entangled pair collapses the total quantum state and the quantum state of the distant particle is immediately determined without making any interaction with it. The isolated collapsed quantum state of both particles remains unentangled in the future. An inertial frame of reference moving with a relativistic speed perceives these events differently is space and time and their simultaneity is relative. In this paper, it is shown that the quantum state collapse happens not only in the present but it also happens in the past of the collapse event.

I. INTRODUCTION

Einstein-Podolsky-Rosen (EPR) argued in their seminal paper that quantum mechanics is inconsistent with the principle of locality and notion of reality \[1\]. Therefore, any type of measurement on a particle cannot instantly influence another distant particle. Various theories based on local hidden variables are proposed to explain predictions of quantum mechanics and experimental observations. To test whether the local hidden variable models or quantum mechanics is correct, J. Bell introduced an inequality which cannot be violated if a local hidden variable model is correct \[2\]–\[4\]. The correlations predicted by quantum mechanics are stronger and Bell’s inequality is violated in different experiments \[5\]–\[12\] and also under the strict condition of locality \[13\] i.e. where distant particles are measured independently and simultaneously separated by a spacelike interval. Further experiments of loophole free Bell test are in agreement with quantum mechanics \[14\]–\[23\].

According to the principle of quantum superposition, a quantum particle can be placed in different quantum states at a same instant of time. If any projective measurement is performed to measure components of a quantum superposition state then the quantum superposition state collapses randomly to one of its components. The quantum state collapse is supposed to happen instantly. It is also shown experimentally that a quantum superposition state collapses almost instantly even if the quantum superposed states are separated far apart \[24\]–\[25\]. However, the notion of same instant of time or simultaneity change in different inertial frames of reference moving with the relativistic speed \textit{w.r.t} each other \[26\]. The nonlocal collapse of a quantum entangled state is supposed to happen instantly and collapsed quantum state remains unentangled in the future of the collapse event in the frame in which the measurement is performed. Since simultaneity is relative therefore, a relativistically moving inertial frame of reference perceives the collapse of separated particles at different spacetime locations. The relativistically moving frame of reference can perceive two particles simultaneously where one of them is existing in the past of the collapse event \textit{w.r.t.} a stationary frame of reference. An important question arises here, does that mean the collapse of a quantum entangled state also happens in the past? This question is analyzed in this paper and it is shown that this is true.

This paper analyzes the question through the spacetime diagrams of two inertial frames of reference, where one of them is moving with uniform speed without rotation \textit{w.r.t.} another frame of reference. Two polarization entangled photons propagate in the opposite direction and one of them is measured to determine its polarization quantum state. This single particle measurement collapses the quantum entangled state and this same process is analyzed in a different inertial frame of reference moving with a relativistic speed.

II. NONLOCALITY ACTING IN THE PAST

Consider an inertial frame of reference $S'$ moving with uniform velocity $v$ along $x$-axis \textit{w.r.t} an inertial frame of reference $S$. Each frame of reference is associated with a flat spacetime and events are represented by cartesian coordinate systems comprising of coordinates $(x, y, z, ct)$ and $(x', y', z', ct')$ corresponding to $S$ and $S'$, respectively. The spacetime events, from one frame to another, are related by the Lorentz transformations: $x' = \gamma(x - vt)$, $y' = y$, $z' = z$, $t' = \gamma(t - vx/c^2)$, where $c$ is the speed of light and $\gamma = 1/(1 - v^2/c^2)^{1/2}$. Consider, a pair of polarization entangled photons with $|\Psi\rangle_{12} = \frac{1}{\sqrt{2}}(|z\rangle_1|y\rangle_2 - |y\rangle_1|z\rangle_2)$, is emitted simultaneously around a spacetime location $(x_o, ct_o)$ in $S$ with same energy and propagation in the opposite direction. Where $|y\rangle_j$ and $|z\rangle_j$ represent a linear polarization state of photon-$j$ along $\hat{y}$ and $\hat{z}$, respectively. Since photon is

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To understand the concept, consider a spacetime diagram representing events w.r.t. \( S \) and \( S' \) as shown in Fig. 1. Consider only the \( x - ct \) of \( S \) and \( x' - ct' \) of \( S' \) planes since other spatial dimensions are unaffected by the Lorentz transformations. The coordinate transformation from \( S \) to \( S' \) follows the hyperbolic geometry, which is a result of invariance of quantity \( x^2 - (ct)^2 = x'^2 - (ct')^2 \). Space and time coordinate axes are calibrated by using this invariance. Speed of photons is invariant in all inertial frames.

FIG. 1. Spacetime diagram representing measurement effect on quantum entangled photons in \( S \) and \( S' \) connected by the Lorentz transformations.
ets representing photons propagating in opposite direction and can be reduced to Dirac delta functions by squeezing the wavepacket in the spatial domain such that \( \psi_1(x, t) \to \delta_1(x - x_0 - ct) \) and \( \psi_2(x, t) \to \delta_2(x - x_0 + ct) \). Total quantum state of photons in \( S \) is a product to their external and polarization state such that \( |\Phi\rangle_{12} = \psi_1(x_1, t_1)\psi_2(x_2, t_2)|\Psi\rangle_{12} \). In \( S' \), total quantum state of photons is \( |\Phi'\rangle_{12} = \psi'_1(x'_1, t'_1)\psi'_2(x'_2, t'_2)|\Psi'\rangle_{12} \).

Consider photon-1 arrives at a stationary polarization sensitive single photon detector \( d_s \) in \( S \) at a spacetime location \((x_d, c_t_d)\) as shown in Fig. 1. The interaction of photon with the detector is represented by the intersection of their respective worldlines. Prior to any polarization measurement, the quantum state of both photons which is a pure state, is polarization entangled in \( S \) and \( S' \). However, as a consequence of quantum entanglement the polarization state of an individual photon is completely random which represented by a mixed state. If after the interaction of photon with the detector the detector output goes high then the location and the polarization state of photons are measured. The detection collapsed the polarization entangled state to \(|y_1\rangle_{1}|z_2\rangle_{2}\) and this collapse effect is simultaneous in \( S \) and polarization state of photon-2 is immediately determined to be \(|z_2\rangle\) without making any contact and measurement on it. In \( S \), collapse happens at a point \( d \) of spacetime coordinates \((x_d, c_t_d)\) and spooky action happens at the same time at a point \( b \) along the line of simultaneity \( c_t = c_s \), where a constant \( c_s = c_t_d \). On the other hand, if photon-1 is transmitted through the detector then the detector state remain unchanged and the polarization state of photons is collapsed on to \(|z_2\rangle_{1}|y_2\rangle_{2}\), this is a complete interaction free measurement. In this case, the quantum state of photon-2 is immediately determined to be in \(|y_2\rangle\) without any making any interaction with photons. The action of measurement simultaneously determines the quantum state of separated photons. However, simultaneity is relative and different inertial frames of reference have different time simultaneity as shown in Fig. 1. The lines of simultaneity where the time coordinate is kept constant are different i.e. \( c_t = c_s \) for \( S \) and \( c'_t = c'_s \) for \( S' \). Events which are simultaneous in one inertial frame of reference are not simultaneous in the other.

In \( S \), measurements on the polarization entangled photons produce \( \langle\Psi|\hat{a}'_3^{(1)} \otimes \hat{b}^{(2)}|\Psi\rangle_{12} \) and \( \langle\Psi|\hat{a}'_3^{(1)} \otimes \hat{a}^{(2)}|\Psi\rangle_{12} = 0 \), \( \langle\Psi|\hat{b}'_3^{(1)} \otimes \hat{b}^{(2)}|\Psi\rangle_{12} = 0 \), \( \langle\Psi|\hat{a}'_3^{(1)} \otimes \hat{a}^{(2)}|\Psi\rangle_{12} = 0 \). Consider photon-1 at a stationary polarization sensitive detector \( d_s \) at a spacetime point \( b \) after the state collapse by \( d_s \) at a point \( d \). The detector \( d'_s \) is also a polarization sensitive detector aligned such that its output goes high if a photon-1 is in quantum state \(|z'_1\rangle\) which is a same state as \(|z_1\rangle\) with an additional phase. Here, the detectors \( d_s \) and \( d'_s \) are aligned such that the transmitted quantum state of photon-1 by \( d_s \) is completely detected by \( d'_s \) and its orthogonal component is transmitted. Detectors can be inserted in the path of photon-1 from a plane orthogonal to direction of velocity of \( S' \) to circumvent their collision. Therefore, \( d'_s \) definitely detects photon-1 if it is in a quantum state \(|z'_1\rangle\). If \( d'_s \) is not placed in the path of photon-1 then photon-1 intersects with the line of simultaneity of \( S' \), at a point \( f \), passing through the point \( b \). If detector location \( x'_e \) is chosen such that its worldline intersects with the worldline of photon-1 between the points \( d \) and \( b \) at an arbitrary point \( e \) then a corresponding simultaneous location of photon-2 lies in the past w.r.t. the point \( b \) i.e.
located on the worldline of photon-2 between the points a and b in S. However, in this past photon-2 was quantum entangled with photon-1 but in S’ quantum state of photon-1 is definitely known to be |z’⟩1 even if detector d’ is not placed. Since photons were quantum entangled in all inertial frames therefore, the quantum state of two photons after the collapse in S’ should be |z’⟩1|y’⟩2. This is possible if quantum state of photon-2 is nonlocally collapsed in S not only at b but the collapse also happened in the past. Otherwise a quantum state after the collapse will be different than the component of the quantum entangled state in S’ with photon-1 in a pure state and photon-2 in a mixed state and Bell’s inequality will always be satisfied. Furthermore, the essence of quantum entanglement is strengthened by a random choice of measurement basis. If on the other hand, d’ is aligned to measure d’1 for photon-1 after the emission of photons and |d’⟩1 is measured then the polarization entangled state is collapsed on to |d’⟩1|d’⟩2 at simultaneous points d and b in S. In S’, polarization entangled state is collapsed on to |d’⟩1|d’⟩2, where |d’⟩1|d’⟩2 is the past quantum state w.r.t. the collapse event at d in S. Thus the spooky action at a distance also acts in the past.

The spacetime locations of events in S and S’ can be evaluated by the Lorentz transformations. In S, the spacetime coordinates, or mean spacetime coordinates for a photon wavefunction of finite extension in spacetime, of a point d are (x_d, ctd) and of b are (x_b, ctd), where x_d = x_o + ctd and x_b = x_o − ctd, these points are located on the line of simultaneity ct = ctd of S. In S’, the spacetime coordinates of d are x_d’ = γ(x_d − vt_d), t_d’ = γ(t_d − vx_d) and of b are x_b’ = γ(x_b − vt_b), t_b’ = γ(t_b − vx_b). A space interval between a and d in S’ is (x_d’−x_a’)^2 = (x_d−x_a)^2 − c^2(t_d−t_a)^2. Since points d and a are located on the line of simultaneity ct’ = ctd’ in S’ therefore, their time coordinates t_d’ = γ(t_d − vx_d) and t_b’ = γ(t_b − vx_b) are same. Thus, the past time interval in S is t_d−t_a = γ(x_d−x_a). For arbitrary velocity v < c, the maximum time interval of past is the time difference between the detection and emission events of photons in S and in this interval the total entangled quantum state is also collapsed instantly with the collapse event d.

III. CONCLUSION

In conclusion, it is shown that the nonlocal collapse of an entangled quantum state happens not only in the present and proceeds in the future but it also happens in the past of the collapse event in an inertial frame of reference in which the measurement is performed. A relativistically moving inertial frame of reference can access the past of the distant photon which has already happened in the other frame. From the nonlocal collapse of quantum entanglement and relative simultaneity it is concluded that the nonlocal collapse of a quantum state of the distant photon also happens in the past of the collapse event.

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Contribution of authors

Idea is conceived by MS and manuscript is written by MS.

[1] Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. 47, 777–780 (1935).
[2] Bell, J. S. On the Einstein-Podolsky-Rosen paradox. Physics Physique Fizika 1, 195–200 (1964).
[3] Bell, J. & Aspect, A. Speakable and unspeakable in quantum mechanics: Collected papers on quantum philosophy (1987).
[4] Clauser, J. F., Horne, M. A., Shimony, A. & Holt, R. A. Proposed experiment to test local hidden-variable theories. Phys. Rev. Lett. 23, 880–884 (1969).
[5] Freedman, S. J. & Clauser, J. F. Experimental test of local hidden-variable theories. Phys. Rev. Lett. 28, 938–941 (1972).
[6] Aspect, A., Grangier, P. & Roger, G. Experimental realization of Einstein-Podolsky-Rosen-Bohm gedankenexperiment: A new violation of Bell’s inequalities. Phys. Rev. Lett. 49, 91–94 (1982).
[7] Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell’s inequalities using time-varying analyzers. Phys. Rev. Lett. 49, 1804–1807 (1982).
[8] Kwiat, P. G. et al. New high-intensity source of polarization-entangled photon pairs. Phys. Rev. Lett. 75, 4337–4341 (1995).
[9] Fry, E. S. & Thompson, R. C. Experimental test of local hidden-variable theories. Phys. Rev. Lett. 37, 465–468 (1976).
[10] Shih, Y. H. & Alley, C. O. New type of Einstein-Podolsky-Rosen-Bohm experiment using pairs of light quanta produced by optical parametric down conversion. Phys. Rev. Lett. 61, 2921–2924 (1988).
[11] Hagley, E. et al. Generation of Einstein-Podolsky-Rosen pairs of atoms. Phys. Rev. Lett. 79, 1–5 (1997).
[12] Ou, Z. Y. & Mandel, L. Violation of Bell’s inequality and classical probability in a two-photon correlation experiment. Phys. Rev. Lett. 61, 50–53 (1988).
[13] Weihs, G., Jennewein, T., Simon, C., Weinfurter, H. & Zeilinger, A. Violation of Bell’s inequality under strict Einstein locality conditions. Phys. Rev. Lett. 81, 5039–5043 (1998).
[14] Hensen, B. et al. Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres. *Nature* **526**, 682–686 (2015).
[15] Rowe, M. A. et al. Experimental violation of a Bell’s inequality with efficient detection. *Nature* **409**, 791–794 (2001).
[16] Matsukevich, D. N., Maunz, P., Moehring, D. L., Olmschenk, S. & Monroe, C. Bell inequality violation with two remote atomic qubits. *Phys. Rev. Lett.* **100**, 150404 (2008).
[17] Ansmann, M. et al. Violation of Bell’s inequality in josephson phase qubits. *Nature* **461**, 504–506 (2009).
[18] Giustina, M. et al. Bell violation using entangled photons without the fair-sampling assumption. *Nature* **497**, 227–230 (2013).
[19] Christensen, B. G. et al. Detection-loophole-free test of quantum nonlocality, and applications. *Phys. Rev. Lett.* **111**, 130406 (2013).
[20] Brunner, N., Cavalcanti, D., Pironio, S., Scarani, V. & Wehner, S. Bell nonlocality. *Rev. Mod. Phys.* **86**, 419–478 (2014).
[21] Garg, A. & Mermin, N. D. Detector inefficiencies in the Einstein-Podolsky-Rosen experiment. *Phys. Rev. D* **35**, 3831–3835 (1987).
[22] Simon, C. & Irvine, W. T. M. Robust long-distance entanglement and a loophole-free Bell test with ions and photons. *Phys. Rev. Lett.* **91**, 110405 (2003).
[23] Tapster, P. R., Rarity, J. G. & Owens, P. C. M. Violation of Bell’s inequality over 4 km of optical fiber. *Phys. Rev. Lett.* **73**, 1923–1926 (1994).
[24] Tittel, W., Brendel, J., Zbinden, H. & Gisin, N. Violation of Bell inequalities by photons more than 10 km apart. *Phys. Rev. Lett.* **81**, 3563–3566 (1998).
[25] Fedrizzi, A. et al. High-fidelity transmission of entanglement over a high-loss free-space channel. *Nat. Phys.* **5**, 389–392 (2009).
[26] Salart, D., Baas, A., Branciard, C., Gisin, N. & Zbinden, H. Testing the speed of ‘spooky action at a distance’. *Nature* **454**, 861–864 (2008).
[27] Yin, J. et al. Lower bound on the speed of nonlocal correlations without locality and measurement choice loopholes. *Phys. Rev. Lett.* **110**, 260407 (2013).
[28] Garrisi, F. et al. Experimental test of the collapse time of a delocalized photon state. *Sci.Rep.* **9**, 11897 (2019).
[29] Einstein, A. Zur elektrodynamik bewegter körper. *Annalen der Physik* **322**, 891–921 (1905).