

Quantum coherence to interstellar distances

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Quantum coherence could be sustained up to interstellar distances. It is shown that the photon mean free path in certain regions of the electromagnetic spectrum, such as within the radio or x-ray ranges, could allow sustaining of the quantum state of a photon up to galactic distances. Therefore processes involving quantum entanglement, such as quantum teleportation, could be realized over very long distances in the Milky Way or other galaxies. This is of fundamental interest and offers a new direction in the role of quantum mechanics. Some limited applications of this observation are discussed.

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I. INTRODUCTION

Quantum teleportation experiments in the past couple of decades have shown that quantum entanglement can be maintained over long terrestrial distances. Such experiments have been done for photons propagating through fiber optic cables [1,2] up to distances of order 10 km, through free space close to sea level, up to around a hundred kilometers [3–5], and up to over a thousand kilometers via satellite to ground teleportation [6]. Both through fiber optics and low altitude atmospheric transmission, loss of signal to the medium has limited the distance to which teleportation can be successful. For the satellite-based experiment, where for most of the journey the photons remain at altitudes above ~ 10 km, attenuation loss is substantially less, thus allowing for much longer distance teleportation.

In quantum teleportation [7] two photons are entangled [8,9], and to sustain this state, their individual quantum states must be maintained. Thus long-distance entanglement also means sustaining quantum coherence of the individual photons to long distances. A natural question arising from the success of the long-distance terrestrial quantum teleportation experiments is how far a distance quantum entanglement, thus quantum coherence, can be sustained. This paper makes a brief observation that quantum coherence of photons can be maintained in some energy ranges to very far interstellar distances in space. The primary loss of the photon quantum coherence in the terrestrial atmospheric free-space teleportation experiments has been atmospheric turbulence and other environmental effects like fog, rain, and smoke. These problems are not present in interstellar space, which therefore leaves the primary loss of quantum coherence to be from elementary interaction of the photons with other particles in the medium. This paper examines the potential interactions of a photon in interstellar space and shows they are weak

enough to allow a quantum state of a photon to be maintained to distances from a few parsecs up to the extent of the Galaxy for certain photon energies.

II. QUANTUM TELEPORTATION

As a simple example of quantum teleportation, suppose Alice (A) and Bob (B) are two observers at different locations, and Alice possesses a photon in a quantum state $|\chi\rangle$. Bob is also in possession of a photon. Alice wants to send the complete information about the quantum state $|\chi\rangle$ over to Bob and input it into the photon he possesses, the end result being that Bob's photon is now in exactly the state $|\chi\rangle$. If this were achieved, it is as if Bob has received exactly the photon Alice had in her possession.

To implement quantum teleportation, Alice and Bob first need to establish a shared entanglement with a pair of photons, say, in the Bell state,

$$|\Psi_{AB}^-\rangle = \frac{1}{\sqrt{2}}(|+_{A}-_{B}\rangle - |-_{A}+_{B}\rangle), \quad (1)$$

where $|+\rangle$ and $|-\rangle$ are the two polarization states of the photon and the subscripts A and B correspond to who is in possession of the respective state, Alice or Bob. Alice now has the additional photon in the quantum state, $|\chi_{A'}\rangle = c|+_{A'}\rangle + d|-_{A'}\rangle$, and she wants Bob's photon to be put into this state. This three-particle state then is

$$\begin{aligned} |\Phi_{A'AB}\rangle &= c|+_{A'}\rangle|\Psi_{AB}^-\rangle + d|-_{A'}\rangle|\Psi_{AB}^-\rangle \\ &= \frac{c}{\sqrt{2}}[|+_{A'}\rangle|+_{A}\rangle|-_{B}\rangle - |+_{A'}\rangle|-_{A}\rangle|+_{B}\rangle] \\ &\quad + \frac{d}{\sqrt{2}}[|-_{A'}\rangle|+_{A}\rangle|-_{B}\rangle - |-_{A'}\rangle|-_{A}\rangle|+_{B}\rangle]. \end{aligned} \quad (2)$$

This state can be reexpressed with the two photons possessed by Alice written in terms of a Bell state basis, to give

$$\begin{aligned}
|\Phi_{A'AB}\rangle = & \frac{1}{2} [|\Psi_{A'A}^-\rangle (-c|+B\rangle - d|-B\rangle) + |\Psi_{A'A}^+\rangle (-c|+B\rangle \\
& + d|-B\rangle) + |\Phi_{A'A}^-\rangle (c|-B\rangle + d|+B\rangle) \\
& + |\Phi_{A'A}^+\rangle (c|-B\rangle - d|+B\rangle)], \quad (3)
\end{aligned}$$

where the other three Bell states are $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|+-\rangle + |-+\rangle)$ and $|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|++\rangle \pm |--\rangle)$. Notice that in this change of basis, the states at B now are all related to $|\chi\rangle$ by a unitary transformation, with the first of the above terms being in fact exactly the state $|\chi\rangle$ up to an overall phase of -1 . If Alice now makes an observation of one of the above four Bell states at her side, this will collapse the above wave function. Whichever of the four Bell states she observes, she can communicate that information to Bob via a classical channel which requires just two classical bits of information. Upon receiving that information, which thus can arrive no faster than the speed of light, he will know what state his particle is in. Thus at this point the state $|\chi\rangle$ up to a unitary transformation has been teleported from Alice to Bob. This process has also destroyed that state at Alice's side, consistent with the no-cloning theorem [10]. As quantum teleportation is a linear operation on quantum states, this example of single-qubit teleportation can be extended to teleportation of multiparticle and multiple degrees of freedom [11–20].

To realize quantum teleportation several technical problems must be overcome. First, Bell states need to be created, for which one method is spontaneous parametric down-conversion [21–23]. Bell states also need to be measured, for which some techniques have developed [24,25]. For the created Bell state in this process, both particles of this state need to be given to the two respective observers A and B . If there are any environmental factors that interfere with either of the two particles during their journey to the two observers, the quantum coherence between the two particles will of course be degraded [22,26]. This is the problem to be considered here, from the demands placed due to the ultralong distances required for interstellar propagation of the photons.

III. SOURCES OF DECOHERENCE

The success of teleportation relies on the entangled photons maintaining their individual quantum coherence over the distance between the two participating observers Alice and Bob. If the entangled photons are transmitted in free space, various effects from the medium could potentially damage the entangled state or harm the quantum state engendered on the photons. For free-space transmission within Earth's atmosphere, turbulence and other environmental effects like fog, rain, and smoke are known to effect the photons. This results in absorption of the photons, decoherence or phase distortion, all of which destroy the delicate quantum coherence in the entangled state

[4,5,27,28]. Notwithstanding these potential problems, as already noted free-space teleportation has been achieved at sea level up to distances of ~ 100 km [4,5] and in ground-to-satellite-based tests to distances of ~ 1000 km [6]. In the latter, predominant photon decoherence and turbulence occurs in the troposphere region, within ~ 10 km above sea level.

In interstellar space there are no atmospheric conditions such as fog and other such effects, which are the causes of entanglement loss in the atmosphere. That implies the main source of entanglement loss and decoherence in interstellar space would be from elementary interactions of the entangled photons with particles along their path. There are regions in the interstellar medium of magnetohydrodynamic turbulence, but ultimately it is still the elementary interactions of a photon with the particles in this region that will lead to decoherence effects on it.

The mean free path of a particle is dependent on the interaction cross section σ with another particle and the number density n of the other particles: $l_{mfp} = 1/(n\sigma)$. Interstellar space has a background distribution of hydrogen, electrons, and protons, and there are photons from the cosmic microwave background (CMB). In addition there are also some trace amounts of other elements. The average number density in interstellar space for protons is about one per cm^3 , giving a mass density of $\rho_{ism} = 10^{-21}$ kg/m^3 . For comparison, the mass density of Earth's atmosphere at sea level is $\rho_a = 1$ kg/m^3 . There are considerable variations in the proton number density in the Galaxy, ranging from well below one proton per cm^3 in coronal gas regions, to HI regions with around one per cm^3 , to as high as 10^4 per cm^3 in the HII gas regions, and a few orders of magnitude even higher in the dense H_2 regions [29]. A large fraction of this density is ionized with free electrons and protons and the rest in neutral hydrogen atoms or H_2 molecules.

For a first estimate, utilizing the results of atmospheric entanglement experiments, if one assumed the mean free path difference between the atmosphere and interstellar space simply scales with the density difference, so ignoring any differences in the specific particle content in the two systems, then the mean free path in interstellar space, using the average density of one proton per cm^3 , would scale as $\rho_a/\rho_{ism} \sim 10^{21}$. Using ~ 100 km as the distance that entanglement is empirically known to sustain in the atmosphere at sea level, this would mean in interstellar space it could sustain entanglement to a distance $\sim 10^{23}$ km, which is of order the size of the observable Universe. This is an overestimation because most of the mass density in Earth's atmosphere is composed of neutral particles that will not interact so readily with photons, which interact with charged particles. In interstellar space, where there would be isolated charged electrons, protons, and ions, photons would more readily interact.

The interaction of photons with free electrons or protons at energy below the electron mass is via Thomson

scattering. This energy range implies photons in the x-ray region of the spectrum and below. The Thomson cross section is

$$\sigma_{\text{th}} = \frac{8\pi}{3} \left(\frac{\alpha \hbar c}{mc^2} \right)^2, \quad (4)$$

where $\alpha \approx 1/137$ is the dimensionless fine structure constant, \hbar the Planck constant, c the speed of light, and m the mass of the charged particle with which the photon is scattering. The fine structure constant is a measure of the coupling in quantum electrodynamics (QED) of photons with charged particles, and as it is much less than one it is indicative of the weakness of the interaction. For the electrons in the medium, this gives a cross section of $6.65 \times 10^{-25} \text{ cm}^2$ and for the proton in the medium, their contribution is 6 orders of magnitude smaller. The mean free path of a photon can now be calculated for the different dense regions of the Galaxy. Using the average value for the number density of free electrons or protons in interstellar space, taking $n_e \approx 1/\text{cm}^3$, this leads to

$$l_{\text{th}} = \frac{1}{\sigma_{\text{th}} n_e} \approx 10^{22} \text{ m} \approx 10^6 \text{ parsec}, \quad (5)$$

which is longer than the size of the Milky Way Galaxy. On the other hand, if one looks at the dense parts of the HII gas region, taking $n_e \approx 10^4/\text{cm}^3$, this reduces the mean free path to 10^2 parsec, which is still traversing a substantial distance in the Galaxy.

The other background is of the CMB photons. Their energy density follows from the blackbody expression as $U_{\text{CMB}} = 8\pi^5/(15h^3c^3)(k_B T)^4$. The present-day CMB photons are at a temperature 2.7 K; thus, the number density of CMB photons is approximately $n_{\text{CMB}} \approx U/(k_B 2.7 \text{ K}) \approx 700/\text{cm}^3$. The photon-photon cross section for photons below the electron mass is [30]

$$\sigma_{\gamma\gamma} = \frac{973\alpha^4(\hbar\omega)^6}{10125\pi(mc)^8} (\hbar c)^2, \quad (6)$$

where ω is the center-of-momentum frame energy of the photons and m the electron mass. In this expression α appears to the fourth power, indicating this process is even weaker than Thomson scattering. For the CMB temperature 2.7 K = 2×10^{-4} eV and for an x-ray photon of energy 100 keV, that means $\omega \approx 4.5$ eV so $\sigma \approx 10^{-65} \text{ m}^2$. This implies the mean free path for the x-ray photon due to interaction with the CMB blackbody photons is

$$l_{\text{CMB}} = 1/(\sigma_{\gamma\gamma} n_{\text{CMB}}) \approx 10^{53} \text{ km}, \quad (7)$$

which is much longer than the observable Universe. Our interest here is restricted just within the Galaxy, which means the interaction with CMB photons is negligible.

Electrons and protons, free and bound as hydrogen, as well as photons, are the main background constituents prevalent all over the interstellar medium. The above estimates show that owing to the weakness of QED, for photons propagating through the interstellar medium in the energy range of x rays or lower, their interaction with this background is negligible.

Gas and dust are also distributed through the interstellar medium of the Galaxy. In addition to the dominant distribution of hydrogen, there are also trace amounts of other elements in the interstellar medium, such as helium, carbon, nitrogen, oxygen, neon, etc. Photons will also interact with the trace abundances of these elements through photoabsorption and photoionization. The expressions for these interactions are complicated, but various sources give the interaction cross sections, opacity and the mean free paths in the interstellar medium [31–33]. They find that the interstellar medium is transparent to photons in the radio wave region, energies below $\sim 10^{-3}$ eV with some caveats [34]. This continues into the microwave region. However from the infrared into the visible and ultraviolet regions, the interstellar medium starts to become more opaque due to the interaction of photons at these energies with atoms in the interstellar medium. Then above tens of eV the interstellar medium once again starts to become increasingly transparent. In the lower x-ray region at 100 eV the photon has a mean free path around 10 parsec and for higher energy x-ray photons at 10^4 eV the mean free path is above 10^5 parsec, which is of order the size of the Galaxy. Thus there is a wide range of photon energies both in the radio and microwave and then in the x-ray regions that lead to long mean free paths.

For classical observation this entire range of spectrum can be detected. However for quantum observations, minimizing interactions with the interstellar medium will minimize decohering effects on the delicate quantum coherence the signal may contain. For that purpose, the radio and microwave range and then the x-ray range have advantages. Magnetic fields are also present in the Galaxy with typical strength around a μG . In ionized regions of the interstellar medium, these magnetic fields affect the propagation of electromagnetic waves leading to Faraday rotation and when magnetohydrodynamic turbulence is present also scintillation. These processes affect long-wavelength electromagnetic signals, so have consequences for radio waves but are negligible for x rays [29,35,36]. In summary, this simple analysis shows that, for certain ranges in the electromagnetic spectrum, the quantum coherence of an entangled photon signal could be sustained over vast interstellar distances.

IV. DISCUSSION

This paper has placed focus on the recent successes with long-distance atmospheric quantum teleportation experiments. These experiments are highly suggestive that much

longer distance teleportation could be possible, and this paper has explored that possibility. Using only known empirical information, we have been able to deduce that quantum teleportation and more generally quantum coherence can be sustained in space out to vast interstellar distances within the Galaxy. The main sources of decoherence in the Earth-based experiments, atmospheric turbulence and other environmental effects like fog, rain, and smoke, are not present in space. This leaves only the elementary particle interactions between the transmitted photons and particles present in the interstellar medium. For the most prevalent particles distributed over the interstellar medium, free electrons, protons, and CMB photons, their interactions with a propagating photon were computed and extremely long mean free paths were found. Other particles in the interstellar medium have only trace abundances but can have much stronger interactions with photons. Such interactions have been extensively studied in the literature, and those results can be transferred over and be applied to the problem studied in this paper. Clearly the same reasoning can apply to examine quantum teleportation and quantum coherence at intergalactic or cosmological distances as well as at energies higher than the x-ray range.

This paper utilized quantum teleportation as the main example, but there are many other protocols requiring quantum coherence to be sustained over spatial distance, such as quantum key distribution [37], superdense coding [38], and also variants of quantum teleportation such as remote state preparation [39]. Alternatively photons in quantum states could just be individually propagating. The considerations in this paper would apply to all such cases.

Aside from the energy of the photon, other factors also dictate the extent of decohering effects on its quantum state. There can be differences in how quantum coherence of the individual particles versus the entanglement between the particles respond to decohering effects [40–42]. Specific entangled states have also been shown to respond differently to decohering effects with some more robust to withstand these effects [43]. Electromagnetic radiation from astrophysical sources will be macroscopic, so contain large numbers of photons. Even though we have shown that photons within certain energy bands have large mean free paths through the interstellar medium, just due to the macroscopically large number of photons present in any radiation field emitted from an astrophysical source, some will inevitably interact with the medium. This will lead to incoherent Thomas scattering events but for some wavelengths could also lead to identifiable collective behavior such as Faraday rotation or scintillation. In the terrestrial quantum teleportation experiments discussed at the start of the paper, decohering effects are a common problem that degrade signal fidelity and so must be properly accounted for at the receiving end, when measuring for the quantum

signal. Similarly any conceivable quantum astronomy experiment would have to account for decohering effects. This decoherence problem is only further complicated by the fact the Galaxy is not homogeneous and isotropic. Depending on the direction a signal is being sent, it will experience varying environments of dust and other features. All such factors will be relevant in determining the extent to which quantum coherence can be maintain on galactic distance scale. The main observation made in this paper is that, for certain ranges of photon energies, the mean free path of such photons is so large in the interstellar medium that a large portion of such photons would nevertheless not decohere. They would remain in their initial quantum state at the receiving end if they were initially placed in one at the point of emission.

The considerations in this paper are of fundamental interest in relation to the role of quantum mechanics on astrophysical scales. Immediate application of these results is limited but there are a few possibilities. There are some examples of quantum behavior exhibited by astrophysical bodies. The considerations of this paper suggest any associated quantum correlations emitted from these bodies in electromagnetic signals might remain intact over the long transmission distances in space. Therefore in addition to any classical signatures, if such signals retained quantum properties, those might be measurable with apparatus based on Earth or space-based near Earth.

One example of a source that could be producing quantum coherent signals is the nonthermal radio filament found near the center of the Milky Way Galaxy, with one interpretation being it is a light superconducting cosmic string [44]. Similar observation of filaments near the center of the Galaxy have been made before [45]. If they were superconducting cosmic strings [46,47], they would lead to electromagnetic effects which would have macroscopic observables but also underlying quantum signatures.

Recently the thermal light from the Sun was used to test quantum interference with a photon sourced in the laboratory [48,49], with the same test also tried with the nearby extrasolar star Sirius. This showed that two photons that are sourced at astronomical distances apart exhibit quantum interference, thus testing the underlying quantum nature of photons and their indistinguishability. The suggestion in our paper here goes further, that in some cases the actual quantum states of photons can be preserved over the long transmission distances of interstellar space. A more distant possibility is tests could be done to probe into the quantum features of Hawking radiation for primordial black holes. Such black holes also have been suggested can create lasing effects [50], for which, beyond its classical electromagnetic signal, its quantum features could be probed. All these possibilities suggest a new type of astronomy looking at quantum features in astrophysical systems.

In a different direction, the results in this paper imply the quantum communication processes that are showing

success in Earth-based tests would also work and to much greater distance in space. For near-space applications, such as within the Solar System, this can already be inferred, but what is more unexpected is that such communication methods could be applicable even at interstellar distances. The one possible application of immediate interest this suggests is attempts at searching for intelligent extraterrestrial communication signals could come from a quantum

communication mode rather than the classical communication modes that have been the only focus up to now.

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